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THESIS

**MARITIME PROTECTION OF
CRITICAL INFRASTRUCTURE ASSETS
IN THE CAMPECHE SOUND**

by

Felix Martinez Tiburcio

December 2005

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This research analyzed and evaluated the Mexican Navy's allocation of surveillance and interdiction resources assigned to the Campeche Sound. The data was obtained via an agent-based simulation, implemented through the use of the software program Map Aware Non-uniform Automata (MANA). The simulation model includes the presence of terrorist boats attacking oil platforms, the Navy resources in the area, service-provider ships in the Sound, and fishing boats that often penetrate into the Sound's exclusion and prevention zones.

From the study is concluded that: the most important threat factor in the scenarios is the speed of the enemy boats; and, with its broad surveillance and communication capabilities, the HAWKEYE is the most important navy resource in the area. The results also provide an operational guide to allocate the Navy units in the Campeche Sound.

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**MARITIME PROTECTION OF
CRITICAL INFRASTRUCTURE ASSETS
IN THE CAMPECHE SOUND**

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Submitted in partial fulfillment of the
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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. Every effort has been made within the time available to ensure that the programs are free of computational and logical errors. Still, they cannot be considered validated. Thus any application of these programs without additional verification is at the risk of the user.

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LIST OF KEYWORDS, SYMBOLS, ACRONYMS AND ABBREVIATIONS

ABM	Agent-Based Model
AEW	Airborne Early Warning
CNA	Center for Naval Analysis
COA	Courses Of Action
CSV	Comma-Separated Values
EEZ	Exclusive Economic Zone
LH	Latin Hypercubes
MANA	Map Aware Non-uniform Automata
MHPCC	Maui High Performance Computer Center
MOE	Measure Of Effectiveness
MPA	Maritime Patrol Aircraft
NPS	Naval Postgraduate School
NOLH	Nearly Orthogonal Latin Hypercube
OLH	Orthogonal Latin Hypercube
PA	Project Albert
PEMEX	Petroleos Mexicanos
SA	Situational Awareness
SEED	Simulation Experiment and Efficient Design

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EXECUTIVE SUMMARY

The Campeche Sound is an area of great economic importance to Mexico: more than 83 percent of the petroleum produced in Mexico comes from there. Its strategic value and economic potential make it imperative that Mexico maintain petroleum production in the Campeche Sound. In light of the 9/11 terrorist attacks in the United States, Mexico cannot discount the possibility of an attack on its strategic facilities, especially those located in the Campeche Sound.

Today, PEMEX and the Mexican Navy maintain mutually supportive security strategies in the Campeche Sound. Prevention and exclusion areas have been established. In the prevention area, there is a system of access control for all boats. In the exclusion area, the authorized navigation of boats to the facilities is allowed only after being verified by units of the navy.

As a solution, the Mexican Navy has created the Sound Task Force III, whose mission, in conditions of green alert (low risk of a terrorist attack), is to carry out naval operations in the marine and coastal zones of the Sound. The Task Force's purpose is to prevent groups from carrying out acts of sabotage and terrorism against the strategic marine and terrestrial facilities involved in the extraction and refinement of hydrocarbons.

During a state of green alert, the force deployment in the operational area consists of the following:

- One HURACAN-class missile ship, SAAR 4.5, with a shipborne helicopter.

- Four POLARIS-class interceptor patrols.

- An E-2C HAWKEYE Airborne Early Warning (AEW) aircraft.

- A C-212 AVIOCAR Maritime Patrol Aircraft (MPA).

- An intercepting aircraft, type REDIGO.

- One helicopter, type MI-17, allocated on one of the platforms.

In our research we developed a simulation using an agent-based model (ABM) that represents sixty possible scenarios depicting the Navy resources in the area and seventeen possible scenarios depicting potential enemies. The scenarios consist of one, two, or three terrorist fast-boats, or red-force boats, each of which is attempting to destroy an oil platform with explosives (kamikazes). Figure 1 shows the terrorist boats, all the resources of the Mexican Navy, and all the service providers' ships that work in the area. In addition, the fishing boats that constantly try to penetrate the preventive zone to fish can be seen. A success in stopping the boats' attack occurs when at least one Navy resource intercepts and kills the small boats within its weapons' range with no damage to the hydrocarbon facilities.

From one to three platforms can be destroyed, depending on the number of enemy boats (up to three). The Measure of Effectiveness is the probability that at least one platform is destroyed.
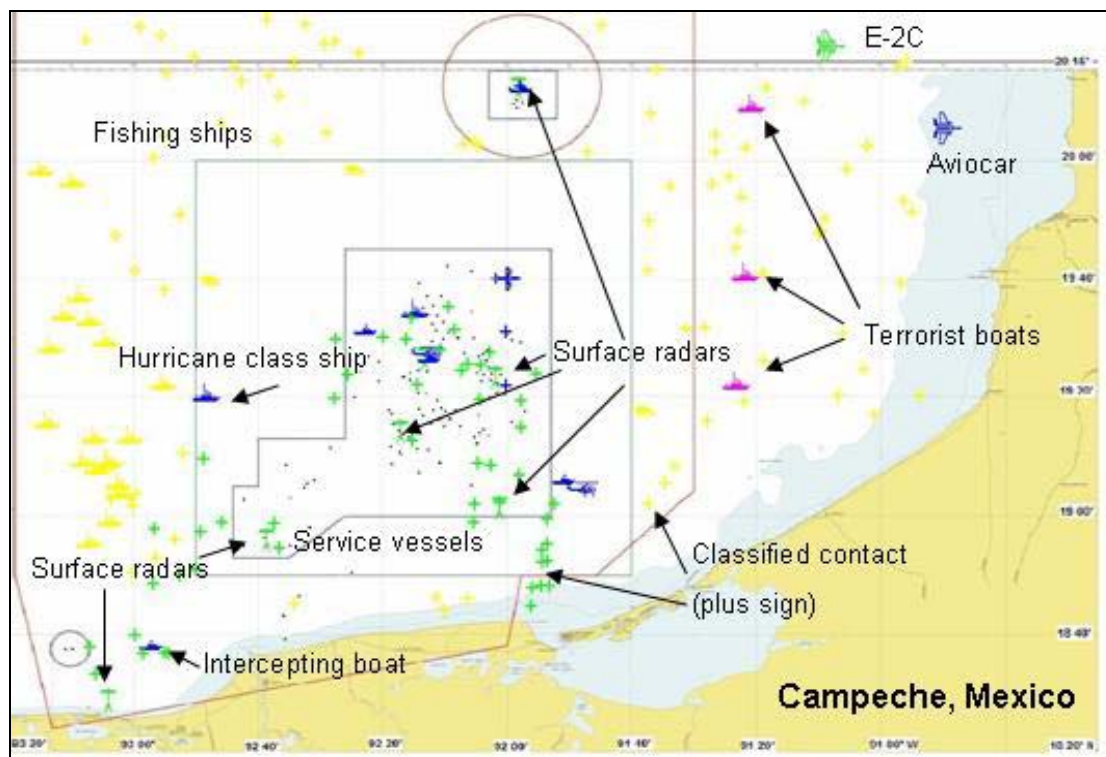
Figure 1.   Map of the scenario in the Campeche Sound. (best viewed in color).

The purpose of this research is to explore various scenarios the Mexican Navy could face in protecting critical assets in the Campeche Sound. Each scenario differs from the others in both the naval resources present in the area and the uncontrollable factors that could be present during a terrorist attack.

This study analyzes the data obtained by the simulation of multiple runs of each possible scenario of the Mexican Navy and the seventeen possible scenarios of the terrorist boats and fishing ships in the forbidden area during a terrorist attack. The data is analyzed in two parts: the full model that analyzes all the controllable and uncontrollable factors in the model and a subgroup of the data that only has the controllable factors in the model.

This study uses three analysis techniques to look at the probability of the enemy destroying at least one platform: Classification trees, Regression analysis, and the one-way analysis of means of each of the critical factors in the model. The critical insights are summarized in two sections: With all the critical factors and only with the controllable factors.

Critical Factors in the full model

The important insights found analyzing the full model are summarized in the following list:

- The most important factor in the probability of destroying at least one platform is the speed of the terrorist boats. The speed limits the time of the Mexican Navy to react.

- When the HAWKEYE AEW aircraft is present in the area, there is a significant increase in the probability of destroying the terrorist boats, no matter the number and speed of the terrorist boats.

- The probability of killing enemy terrorist boats before they reach an oil platform decreases when more than two fishing boats are in the maritime prevention area during a terrorist boat attack.

Critical Controllable Factors

During the analysis of the data subgroup, which only includes the controllable factors (Navy resources), we gleaned several important aspects of the model:

- Because of its long range surveillance radar for detection and classification, and significant communication capability, the HAWKEYE AEW aircraft is the most important of the controllable factors.

- When the HAWKEYE AEW aircraft is absent in the scenario, it is important that the AVIOCAR MPA (which serves in a very similar role as the HAWKEYE AEW aircraft, but with less range in its surveillance radar) be present in the area.

- The patrol area patrolling of the HURACAN ship is not important in the model. Both main patrol areas, the exclusion area and the maritime prevention area, have the same effect within the model.

- The HURACAN ship is significant in the scenarios only when it carries a shipborne helicopter.

- The additional POLARIS interceptor boats in the area are significant in the probability of destroying the terrorist boats only if the route of the terrorist boats lies within their patrol area.

- The patrol areas of the REDIGO aircraft and the MI-17 helicopter patrolling are not significant in the model. This does not mean that they are not necessary in the scenarios; it means that any of these units' presence in the area has the same effect in the model.

I. INTRODUCTION

A. BACKGROUND

Energy sources are strategic economic and political assets for both producer countries and their clients. Any interruption in the global production and transport of natural resources has severe economic consequences; energy being the most critical commodity. Major importing countries consider protection of that flow a significant national concern. As a result of the 9/11 terrorist attacks in the United States, Mexico, one of the United States' most important suppliers of oil, cannot discount the possibility of an attack on its strategic facilities, especially those located in the Campeche Sound.

The Campeche Sound is of great economic importance to Mexico. More than 83 percent of the petroleum operated and produced in Mexico is extracted from that area. Its strategic importance and economic potential make it imperative that Mexico maintain petroleum production capacity in the Campeche Sound.

The portion of the Gulf of Mexico where PEMEX (Petroleos Mexicanos) is active in prospecting, exploration, hydrocarbon production and exportation includes a total surface of 150,000 square nautical miles. PEMEX divided this area in two regions: a northeast region of 50,000 square nautical miles and a southwestern region of 100,000 square nautical miles. There are 243 marine platforms, 1,400 miles of submarine pipelines to transport crude petroleum, natural gas, and nitrogen, a maritime terminal in Dos Bocas and in Cayo Arcas, a ship moored for the storage of crude for exportation, and five monobuoys for the loading of crude oil tankers.

During 2004 PEMEX exported a daily average of 1,844,000 barrels of petroleum, of which 78 percent was sent to the United States. The remaining 22 percent was distributed to Europe, the Far East, and the rest of the Americas.

The Mexican Navy is a national military institution, whose mission is to use the naval supremacy of the Federation for exterior defense and homeland security. Among its multiple responsibilities are:

- Take actions to safeguard Mexico's national sovereignty and to defend the integrity of its national territory in the territorial sea, marine-terrestrial zone, islands, keys, reefs, and continental shelf; as well as in its inner waters, lakes, and rivers in their navigable parts and corresponding airspace;

- To guard Mexico's sovereign rights in the Exclusive Economic Zone (EEZ); and

- To protect Mexico's strategic facilities in areas under Navy jurisdiction.

B. ACTUAL SCENARIO IN THE CAMPECHE SOUND

Today PEMEX and the Mexican Navy employ a strategy of mutual support in maintaining the security of petroleum production in the Campeche Sound. An Aerial Prevention Zone, two Maritime Prevention Zones, and three Exclusion Zones are established (Figure 2). PEMEX and the Mexican Navy use these geographically defined zones to control activity near petroleum production facilities. The Aerial Prevention Zone is mentioned here to fully describe the control regime, though it is not used in modeling later in this thesis.
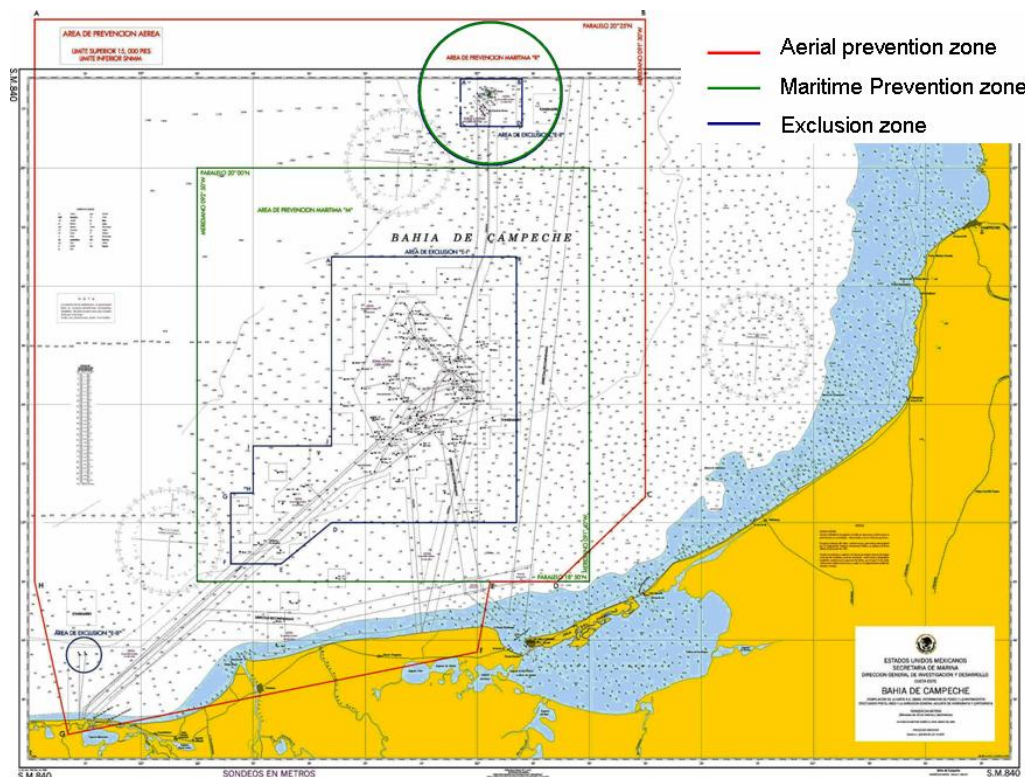
Figure 2.   Areas of Prevention and Exclusion in the Campeche Sound.
(best viewed in color).

The Aerial Prevention Zone covers a polygon with an area of 14,600 square nautical miles, formed by the lines between the vertices listed in Table 1.

Vertex	Lat. North	Long. West
A	20° 25' 00"	093° 19' 00"
B	20° 25' 00"	091° 30' 00"
C	19° 04' 20"	091° 30' 00"
D	18° 50' 00"	091° 45' 42"
E	18° 50' 00"	091° 57' 40"
F	18° 38' 00"	092° 00' 00"
G	18° 24' 00"	093° 13' 00"
H	18° 50' 00"	093° 19' 00"

Table 1.   Geographic Positions of the vertices of the Aerial Prevention Zone.

The vertical limits of the polygon are established from the mean sea level to 15,000 feet.

The Maritime Prevention areas constitute the areas M and R. Area M includes a rectangle with an area of 6,100 square nautical miles, formed by the parallels 18° 50' 00" N and 20° 00' 00" N and meridians 092° 50' 00" W and 091° 40' 00" W. Area "R" includes a circular surface of 450 square nautical miles with a radius of 12 nautical miles, whose center lies in the position Lat. 20° 12' 00" N and Long. 091° 57' 30" W.

PEMEX and the Navy of Mexico continually monitor all activity in the Maritime Prevention Zones. The Navy identifies and controls all maritime and aerial traffic that enters these zones. Fishing vessels are permitted rapid, uninterrupted transit through the Maritime Prevention Zones to fishing areas outside controlled areas after receiving authorization. No other activity is permitted except that required for oil exploration and production.

The Area of Exclusion is an area in which no traffic of boats or airships is allowed, except that required for the operation of the oil platforms. It is

constituted by areas E-1, E-2, and E-3. Area E-1 includes a polygon with an area of 2,200 square nautical miles, formed by the union of the vertices listed in Table 2.

Vertex	Lat. North	Long. West
A	19° 45' 00"	092° 26' 00"
B	19° 45' 00"	091° 53' 00"
C	19° 00' 00"	091° 53' 00"
D	19° 00' 00"	092° 26' 00"
E	18° 53' 00"	092° 35' 00"
F	18° 53' 00"	092° 44' 00"
G	19° 05' 00"	092° 44' 00"
H	19° 05' 00"	092° 40' 00"
I	19° 13' 00"	092° 40' 00"
J	19° 13' 00"	092° 26' 00"

Table 2.   Geographic Positions of the Vertices of Exclusion Zone E-1.

Area E-2 includes a polygon with an area of 110 square nautical miles, conformed by the vertices listed in Table 3.

Vertex	Lat. North	Long. West
A	20° 15' 00"	092° 03' 00"
B	20° 15' 00"	091° 52' 00"
C	20° 07' 00"	092° 03' 00"
D	20° 07' 00"	091° 52' 00"

Table 3.   Geographic Positions of the Vertices of Exclusion area E-2.

Area E-3 includes a circular surface of 30 square nautical miles with a radius of 3 nautical miles, whose center lies in the position Lat. 18° 37' 30" N and Long. 093° 10' 12" W.

As a solution, the Mexican Navy created the Sound Task Force III, whose mission is to carry out naval operations in the marine and coastal zones of the Campeche Sound in conditions of green alert. The Task Force's purpose is to

prevent transgressors of the law from carrying out acts of sabotage and terrorism that could cause partial or total damage to the strategic marine and terrestrial facilities involved in the extraction and refinement of hydrocarbons.

In a condition of green alert, the force deployment in the operational area consists of the following:

- One HURACAN-class missile ship, with a shipborne helicopter, type PANTHER. It patrols and monitors and interdicts boats that have nothing to do with PEMEX activities in the areas of exclusion.

- Two POLARIS-class interceptor boats, with personnel, embarked as a quick-reaction force, located in the city of Carmen, Campeche. Their mission is interception tasks, operating with the unit, class HURACAN or class Durango.

- A POLARIS-class interceptor boat, operating from Dos Bocas, Tabasco. It carries out operations of interdiction in the exclusion zone E-3.

- An E-2C HAWKEYE Airborne Early Warning Alert aircraft, for early alert and flight control, makes random flights and reports suspicious targets.

- A C-212 AVIOCAR Maritime Patrol Aircraft makes random flights for recognition and monitoring.

- An intercepting aircraft, type REDIGO, which makes flights for monitoring and deterrence.

- One helicopter, type MI-17, allocated on one of the platforms, with tasks of transport and insertion of forces for immediate reaction and flights of recognition in the exclusion areas.

C.   MOTIVATION

The thesis topic was motivated by accounts of recent terrorist attacks on facilities and ships similar to the situation in Mexico's Campeche Sound, where a main oil facility, guarded by the Mexican Navy, could be vulnerable to attacks similar to those described here. In 2000, two such attacks made the Mexican government immediately aware of the potentially dangerous situation in the Sound.

An attempt to bomb the USS *THE SULLIVANS*, for example, one of the millennium attack plots, is now widely seen as a trial run for the subsequent bombing in Yemen of the USS *COLE*. The attack failed when the bombers' boat, overloaded with explosives, began to sink. The bombing of the *COLE* (Figure 3), a guided-missile destroyer, occurred on October 12, 2000. (http://en.wikipedia.org/wiki/USS_Cole_bombing). During Operation Iraqi Freedom, there have also been similar cases of suicide bombers on boats attacking Iraq's main oil facilities.

Figure 3.   USS Cole (DDG-67) in Port Aden on the Arabian Peninsula after was attacked from a small craft in a terrorist act by suicide bombers.

D.   BENEFITS OF THE STUDY

The events of 9/11 were a wake-up call for the international community. Mexico, like many other countries, now must take appropriate actions to prevent similar terrorism attacks on strategically sensitive potential targets in Mexico. It is necessary to take preventive measures and to increase the monitoring of vital facilities. The Mexican Navy has responsibility for and jurisdiction over strategic geographical areas in Mexico. This thesis argues for a more effective scheme of security to protect the critical infrastructure in the Campeche Sound with the resources of the Mexican Navy in the area.

E.   THESIS OVERVIEW

Chapter II provides more information about the capabilities of the different units of the Mexican Navy deployed in the Campeche area, the scenarios explored in this thesis, and performance measures. Chapter III describes how these resources and scenarios are implemented in the agent-based software used in this thesis, Map Aware Non-uniform Automata (MANA). Chapter IV describes the robust experimental design for this study, the implementation of a Nearly Orthogonal Latin Hypercubes crossed with a full factorial design and the results of the simulation. Chapter V explains the data analysis. Chapter VI summarizes all the conclusions of this study.

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II. RESOURCES, CAPABILITIES AND OPERATIONAL SCENARIOS IN THE AREA

A. OVERVIEW

This Chapter describes the capabilities and characteristics of the different units of the Mexican Navy deployed in the area; it describes the operational scenarios of the Mexican Navy, as well as their measures of effectiveness. After this description, it provides a background for the modeling used to investigate the best allocation and effective tactics of the current resources of the Mexican Navy and the additional resources required to enhance the surveillance in the area. Finally, the chapter discusses the agent-based model used in this analysis.

B. MEXICAN NAVY RESOURCES IN THE AREA

The Mexican Navy has a responsibility to provide security and a capacity to respond to possible threats that could come from international terrorism or drug trafficking in the Campeche Sound. Thus, it has created the Sound Task Force III mentioned in Chapter I, which has control of the operations on the surface, and of aerial units and marines in the area. The task force coordinates its security responsibilities with PEMEX.

The task force maintains a permanent unfoldment of two HURACAN-class missile ships, , with a shipborne helicopter type PANTHER for monitoring the maritime and exclusion areas; four POLARIS-class interceptor boats, two deployed in the maritime prevention and exclusion areas, working in coordination with the ships, and one deployed in the areas E-2 and E-3; two aircraft (one E-2C HAWKEYE Airborne Early Warning aircraft and One C-212 AVIOCAR Maritime Patrol Aircraft); two MI-17 helicopters, one based in Campeche and the other on one of the oil platforms; and marines also based on some platforms.

1. E-2C HAWKEYE Airborne Early Warning aircraft

The E-2C HAWKEYE Airborne Early Warning (AEW) aircraft (Figure 4) can detect and process simultaneously up to 600 aerial, surface, or terrestrial targets, at a height of 25,000 feet, from distances out to 300 km. It can operate by day or at night. Its capabilities are showed in Table 4.

Max Speed:	260 knots
Cruise speed:	230 knots
Endurance:	06:00 hr
Avionics:	Doppler-ELDNS, Ins (Cains)-ASN 92, TACAN-ARN 118, radio altimeter-APN 171, reference of course and altitude; HF, VHF (aerial band). Data link
Means of detection:	Aircraft and surface detection radar with range of 250 nautical miles, IFF system

Table 4.   Capabilities of the E-2C HAWKEYE AEW.

This aircraft carries out activities of patrol and marine monitoring, control of aerial and surface targets, analysis of threats and security of the strategic facilities in the Campeche Sound, among others.

Figure 4.   E-2C HAWKEYE Airborne Early Warning aircraft.

2. C-212 AVIOCAR Maritime Patrol Aircraft

The C-212 AVIOCAR Maritime Patrol Aircraft (MPA) is used by the Mexican Navy for functions that include: maritime patrol and surveillance, traffic control, battling drug trafficking and illegal fishing, and search-and-rescue missions in the sea (Figure 5). In addition, eight aircraft AVIOCAR MPA are currently being converted to maritime patrol craft. Two have already been modernized in Spain; the rest are being converted in Mexico. When the conversion is complete, they will have an increased capacity for detection and identification, even in meteorologically adverse conditions and at night, thanks to their new mission systems, consisting of radar, monitoring aerial cameras, integral systems of communication, and mission consoles (Table 5).

Figure 5.   C-212 AVIOCAR Maritime Patrol Aircraft.

The primary mission of the aircraft is to make detection flights to provide an early air-alert and control of the reaction against surface targets. Secondary missions include the following:

- Patrol flights, to detect and identify targets within its area of cover.
- Determining the position, course, and speed of the targets.
- Receiving and transmitting information about the targets, in real time, to other units.
- Vectoring and controlling the intercepting units.
- Search-and-rescue coordination.
- Photography by radar of a defined area or even a moving object.

Maximum Distance	1200 nm
Endurance with maximum fuel	08 hours
Cruise speed	150 nm
Radar	SEA VUE SV-2037 and camera Flir Safire II
Radar range	123 nm
Max number of simultaneous targets	32 (surface)

Table 5.   Capabilities of the C-212 AVIOCAR MPA.

3.   HURACAN-class Missile Ship SAAR 4.5

The two HURACAN-class missile ships (Hurricane in English) showed in Figure 6, recently acquired by the Mexican Navy from Israel, reach a speed of up to 31 knots, have a displacement of 505.9 tons, and have a flight deck to receive PANTHER-type helicopters. They are also equipped with technological weapons systems, capable of detecting any type of target in a typical range of up to 90 nautical miles, resisting attacks and identifying targets.

Figure 6.   HURACAN-class missile ship.

These ships carry two kinds of antiship missiles, two twin launchers for the McDonnell Douglas Harpoon IC in crossover, and two pairs of outboard-angled, forward-facing, launchers for the IAI Gabriel II. They also carry an OTOBREDA 76/62 Compact mounting at the stern and a Vulcan Phalanx Mk-15 forward of the bridge.

4. AS 565 PANTHER Helicopter

The AS 565 PANTHER (Figure 7) is the military version of the Dauphin, and is capable of transporting eight to ten commandos to a combat zone and providing evacuation and logistic support. It is carried on board the ships to improve the vessels' observation, reconnaissance, and attack capabilities well beyond the range of the vessels' systems. It has a cruising speed of 148 knots, a range of 440 nm, and a Browing .50 caliber CDP machinegun.

Figure 7. AS 565 PANTHER Helicopter.

5. POLARIS-class Patrol Interceptor Boat 90H

The POLARIS interceptor boat's design is based on one developed by the Ministry of Defense, Sweden, and adapted to fit the needs of the Mexican Navy (Figure 8). The boat is made entirely of aluminum alloy. It has a .50 caliber machine gun, calibrated at CDP, and is able to reach speeds of more than 40 knots by its water-propulsion jet. There are two versions: the A1, for transporting troops, with a capacity to transfer up to eighteen men with their battle equipment; and the A2, for monitoring and patrolling, with berthing for six men.

Figure 8. POLARIS-class Patrol Interceptor Boat 90H.

6. Helicopter MI-17

The MI-17 is a multirole helicopter (Figure 9) that is used by air-assault infantry forces to attack at a point of penetration, reinforce units in contact, or disrupt counterattacks. Additional missions may include: attack, direct air-support, electronic warfare, airborne early-warning and search and rescue. The helicopter's capabilities are shown in Table 6.

Figure 9.   Helicopter MI-17.

Maximum speed	250 Km/hr
Cruising speed	200 Km/hr
Range	1000 Km
Radars	Maritime surveillance radar RDR1500B (160 nm) and night vision system
Armament	2 x 50 CDP machine guns

Table 6.   Capabilities of the Helicopter MI-17.

7. L-90 TP REDIGO

The L-90 TP REDIGO (Figure 10) is a turboprop-powered military basic trainer aircraft. The aircraft is of conventional configuration, with retractable tricycle undercarriage and a low wing. As is typical with many military trainers, it also can carry light armament for weapons training, or potentially, for use in a close-support role. The aircraft's capabilities are shown in Table 7.

Figure 10.   L-90 TP REDIGO

Maximum speed	352 km/h (220 mph)
Range	1,405 km (878 miles)
Service ceiling	7,620 m (25,000 ft)
Rate of climb	696 m/min (2,280 ft/min)
Armament	2 50 CDP machinegun and 2 rocket launchers

Table 7.   Capabilities of the L-90 REDIGO.

C.   SCENARIO

The term "scenario," as used here, means a depiction of the allocation and patrol surveillance of the different resources of the Mexican Navy in the maritime protection of the strategic facilities in the Campeche Sound against terrorist fast-boat attacks. In this area, there are always a fixed number of navy ships and aircraft, but given their different types of operational functions, the same types of resources are not always in the area at the same time. This study presents sixty combinations of resources, to asses the different capabilities and operational tactics of the various units of the Mexican Navy in the area.

1.   Scenario Description

In the scenario shown in Figure 11, the red force consists of one, two, or three terrorist fast-boats, each of which is attempting to destroy an oil platform

with explosives (kamikazes). In the beginning, the red-force boats travel at the same speed as the fishing boats, hiding among them. If they feel that they are discovered, however, they increase to full speed to reach the target as quick as possible and escape being killed by a unit of the navy. A successful prevention of the small boats' attack occurs when at least one of the navy resources intercepts and destroys a red-force boat within its weapon range, with no damage done to the strategic facilities.
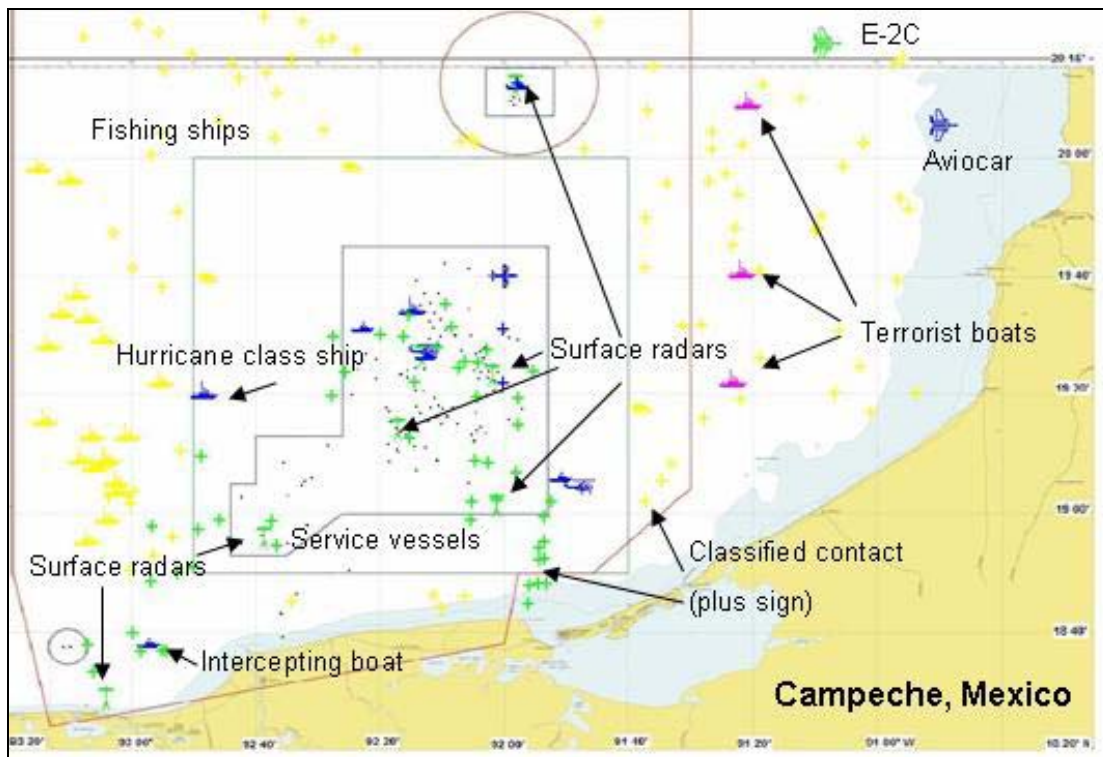
Figure 11.   Map of the scenario. (best viewed in color)

2.   Scenario Background and Initial Conditions

This scenario takes place in the Campeche Bay. It simulates Mexican Navy operations to protect the infrastructure assets in the area, an expanse of more than 20,000 nautical square miles.

A HAWKEYE AEW, or AVIOCAR MPA, departs from Campeche City, sited in the northeast of the bay, and flies over the operational area. The crew's mission is to detect any foreign object in the area, with the AVIOCAR's maritime surveillance radars and provide an early-warning alert to other navy units in the area. The objects are classified as "unknowns." If one of them is traveling at a

suspicious speed, is on a course toward the oil platforms, or penetrates the prevention area, another navy unit, if available, will approach the unknown and determine its clearance classification.

The REDIGO aircraft and MI-17 helicopter conduct a different surveillance patrol above the operation area, to assure that only authorized vessels are in the prevention and exclusion areas. If one of the early-warning aircraft alerts them about a suspicious vessel, one departs from the city of Carmen, an island in the south on the map, and one from Campeche, in the east on the map. The rest of the navy units operate different patrols for the same purpose. The goal of the red forces is to reach and destroy at least one of the oil platforms in the vicinity.

3. Constraints

When fishing boats go into the maritime prevention area, at least one unit of the navy must approach them, to determine their identity as neutral vessels and direct them out of the prevention area. This means that one unit must spend time and effort on a nonenemy contact, when it needs to be prepared to encounter an enemy ship, if necessary.

4. Measure of Effectiveness

a. *Probability of Destroying Red-forces Boats Before They Reach Their Goal*

Because the red forces' goal is to destroy at least one of the oil platforms using different numbers of small fast-boats, their prevention depend on the navy's having a correct selection of units in the area. We want to maximize the probability of successful prevention by selecting the best allocation of units and patrol patterns to deal with both the number and the speeds of the terrorist boats.

D. WHY SIMULATION BY AGENT-BASED MODELS (ABM)?

The military uses analytical methods and a formulation of models to find an optimal solution to potential attack-area problems. "However, because of complexity, stochastic relations, and so on, not all real-word problems can be

represented adequately in closed-formed models. Attempts to use analytical models for such systems usually require so many simplifying assumptions that the solutions are likely to be inferior or inadequate for implementation. Often, in such instances, the only alternative form of modeling and analysis available for the decision maker is simulation" (Winston, 2004).

For this study, simulation is more applicable because analytical models may require us to make many simplifying assumptions. "Simulation may be defined as a technique that imitates the operation of a real-world system as it evolves over time. A simulation model usually takes the form of a set of assumptions about the operation of the system, expressed as mathematical or logical relations between the objects of interest of the system. The simulation process involves executing or running the model through time, usually on a computer, to generate representative samples of the measure of performance" (Winston, 2004).

It would be difficult for analytical methods to simultaneous capture all the important factors that are involved in the scenarios presented in this study. For example, the probability of detection and identification, the differences in the speeds and number of the terrorist boats, weather and atmospheric conditions, as well as the enemy's tactics. "Simulation is most often used to analyze 'what if' types of questions" (Winston, 2004). This research analyzes sixty different models of the Mexican Navy's resources in the Campeche area. Their purpose is to detect different kinds of terrorist fast-boats. The study also analyzes the repercussion of these operations for fishing boats trying to penetrate the prevention or exclusions area for the purpose of fishing, during a possible incursion of terrorists' boats.

Because the models are small, they can be processed very quickly using high-performance computing capabilities. "You get a dynamic combination because you can look at literally thousands, tens of thousands, hundreds of thousands, even millions of runs. You can vary the parameters, which are numerous because in today's uncertain world, you're up against so many

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different factors. You can't really predict anything, but if you look at enough possibilities, you can begin to understand" (Horne, June 2005).

The Marine Corps Warfighting Laboratory's Project Albert (PA) is the research and development effort whose goal is to develop the process and capabilities of data farming, a method for addressing decision-maker's questions that applies high-performance computing to modeling to examine and understand the landscape of potential simulated outcomes, enhance intuition, find surprises and outliers, and identify potential options. Data farming is a method by which potentially millions of data points are explored and captured. It could be considered akin to data mining combined with feedback, which allows for the more intelligent collection of more data points (www.projectalbert.org).

To implement the scenario, it is necessary to use a toolkit for the data-farming environment, in which a distillation model can be executed. In that environment, Project Albert has, among its suite of models, the Map Aware Non-uniform Automata (MANA) software, developed by the New Zealand Defense Technology Agency, which can be used free of charge by members of the PA team. MANA is an agent-based model, in which the agents in the environment are "map aware." This means that the agents' situational awareness includes both the depicted terrain and the battle space activities in the simulation. The term "non-uniform" means that each agent has different behavior parameters and capabilities. The term "automata" means that each agent reacts independently on the battlefield, according to his own situational awareness.

The next chapter describes how the specific scenario in the Campeche Sound is implemented using MANA, explains how each feature in MANA is adapted for the model, and shows how these features help to present realistic-looking behavior.

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III. MODEL DESCRIPTION

This chapter describes how the key features in MANA version 3.0.39 were used to develop an experimental scenario of the Campeche Sound, explained in previous chapters. One of the multiple advantages of MANA is the user's manual, which shows all its features clearly, in an understandable way (MANA: Map Aware Non-uniform Automata, Version 3.0, User's Manual, July 2004). Therefore, this chapter is based on the manual's descriptions, with modifications implemented for this specific scenario.

A. MANA

1. Using MANA

MANA is basically a scenario-exploring model; it does not describe every aspect of particular military operations. When a model is implemented using MANA, there is no "key" that indicates that the model is working perfectly. Therefore, each entity in the model must be set up carefully to ensure that they behave according the user's specifications. Since MANA explores the greatest range of possible outcomes with the least set-up time, it is often only necessary to have simple rules of behavior to achieve the desired results.

2. MANA Versus Other Agent-Based Combat Models

MANA is used primarily as a distillation tool, that is, to create a button-up abstraction of a scenario that captures only the essence of a situation and avoids unessential details. MANA builds on and complements the earlier ISAAC/EINSTEIN CA models developed by the Center of Naval Analysis (www.cna.org), and the now discontinued Archimedes model that was being designed for the U.S. Marine Corps. MANA explores additional key concepts that ISAAC did not explore at that time, in particular:

- Situational Awareness: Two types of situational awareness maps: a squad map that holds direct squad-contact memory and an inorganic map that stores contact memories provided by other squads through communication links.

- Communications: Allows the communication of contact sightings between squads.

- Terrain map: Contains terrain features such as roads that agents can follow.

- Waypoints: Can define a set of waypoints, not merely the final goal.

- Event-driven personality changes: Different events can trigger squads with varying personality sets, which last for a user specified amount of time.

B. MODEL IMPLEMENTATION IN MANA

1. Battlefield

The battlefield used here in MANA is a snapshot of the nautical chart N.O. 28260 "East coast of the Campeche Bay," published by the Investigation and Development Direction of the Mexican Navy. The chart is modified first, in a bitmap editor with different colors, depending on the type of terrain. For instance, in this study we use land, sea, preventive area, exclusion area and, territorial sea.

Figure 12.   Screen of the Scenario Map Editor. (best viewed in color)

This is done because agents in MANA recognize types of terrain and, by this method, the ability of the agents to enter certain regions of the map can be controlled. Next, the chart is imported into MANA as a terrain file, as shown in Figure 12. The original chart starts at the geographical position 19° 20' N, 091° 25' W and finishes at 20° 15' N, 093° 20' W, indicating 175 x 115 nautical miles (nm) of parallels and meridians, respectively. The default battlefield in MANA is a 200 x 200 grid of cells, but to get a better resolution of the scenario, the number of cells is 875 for the X axes or parallels and 625 for the Y axes or meridians: this means that there are five cells for each nautical mile, or each cell covers 400 x 400 yards. To configure the settings of the battlefield, we use the option "Edit Battlefield" in the setup option of the menu bar of MANA. The battlefield settings of the scenario are shown in Figure 13.

Figure 13.   Screen of the MANA Battlefield Settings. (best viewed in color)

The map scale is changed with the values as previously explained; the contact aggregation radius also is changed to one (1) to help to improve the speed of the model and to prevent unnecessary clutter on the map. All other selections are at their default values.

2.   Squads

According to the MANA user's manual, version 3.0.37, a squad is a group of agents sized between 0 and 1000. The agents in a squad share the same properties and can switch between states either individually or as a group. Table 8 shows all the squads used in this study.

Squad #	UNIT	# agents	Alliegance	total entites	total agents
2	Enemy	3	Red	1	3
1	Interceptor in Dos Bocas	1	Blue		
3	Hurricane Ex	1	Blue		
4	Interceptor in Cayo Arcas	1	Blue		
5	Interceptor area E-2	2	Blue		
6	Radar	1	Blue		
7	Radar	1	Blue		
8	Radar	1	Blue		
9	Radar	1	Blue		
10	Radar	1	Blue		
11	Radar	1	Blue		
12	Radar	1	Blue		
13	Service vessels	50	Neutral		
14	Fishing ships	100	Neutral	26	179
15	Interceptor in platform	1	Blue		
16	Aircraft Aviocar C-212	1	Blue		
17	Target 1	1	Blue		
18	Target 2	1	Blue		
19	Target 3	1	Blue		
20	Helicopter Ixtoc	1	Blue		
21	Helicopter Patrolling	1	Blue		
22	Aircraft Redigo	1	Blue		
23	Aircraft E-2C	1	Blue		
24	Hurricane MP	1	Blue		
25	Renegate Fishing ships	5	Neutral		
26	Helicopter Hurricane Ex	1	Blue		
27	Helicopter Hurricane MP	1	Blue		

Table 8.   Squads in the model.

To add or edit the squad properties, we use the "Edit Squad Properties" under the Setup menu. This is MANA's most important feature, both because all the squads in the model are added in this screen and because here is where their behavior is defined. In the menu at the top of the screen, each button opens a different screen (Figure 14) that works to edit a different property of the squad. The *General* button, includes the name of the squad, number of agents in the squad, whether the squad is active or not, and other miscellaneous options that generally remain constant. Near the bottom of the screen are six buttons that allow us to delete, copy or save a squad or save all the squads, so as to use them with the same properties in the same simulation or in another model.
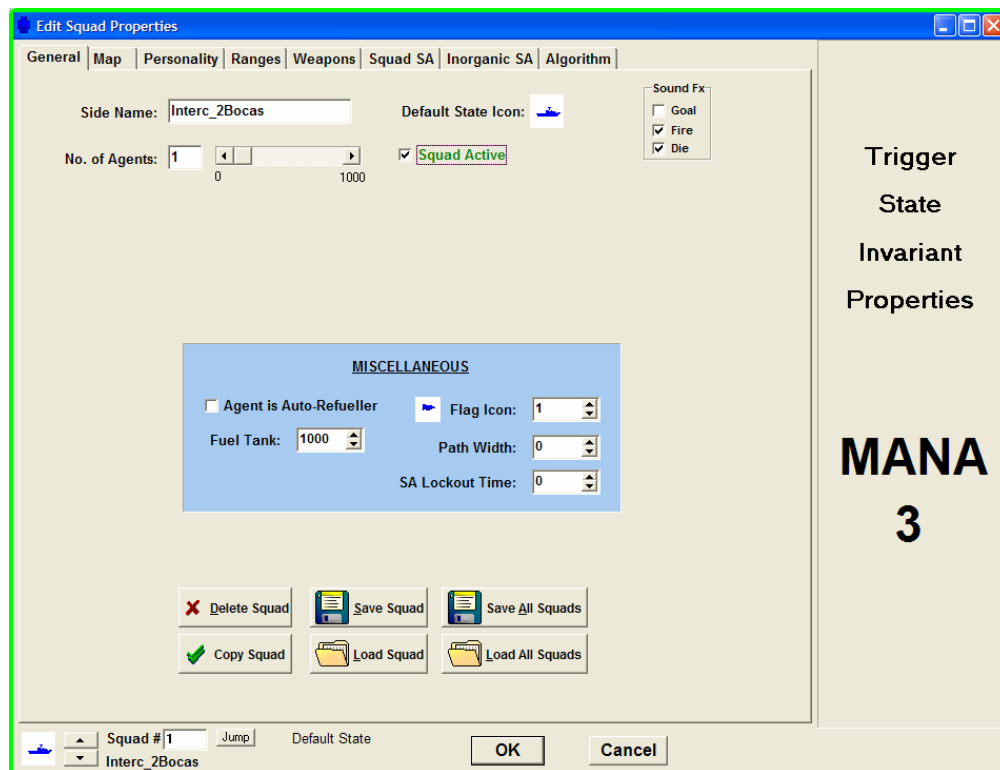
Figure 14.   Screen of the *General* Properties under the "Edit Squad Properties" menu. (best viewed in color)

In this model, there are twenty-seven squads (Table 8), representing all the agents involved in the scenario, some of them with the same properties.

The *Map* button allows a user to assign the squad to areas on the map, to set "home" locations for each squad, and to set waypoints for each group of squads. Figure 15 shows a sample screen setting the home position of a squad and the waypoints of its patrol area. Each squad has a different home position and different waypoints, depending on its role in the simulation.
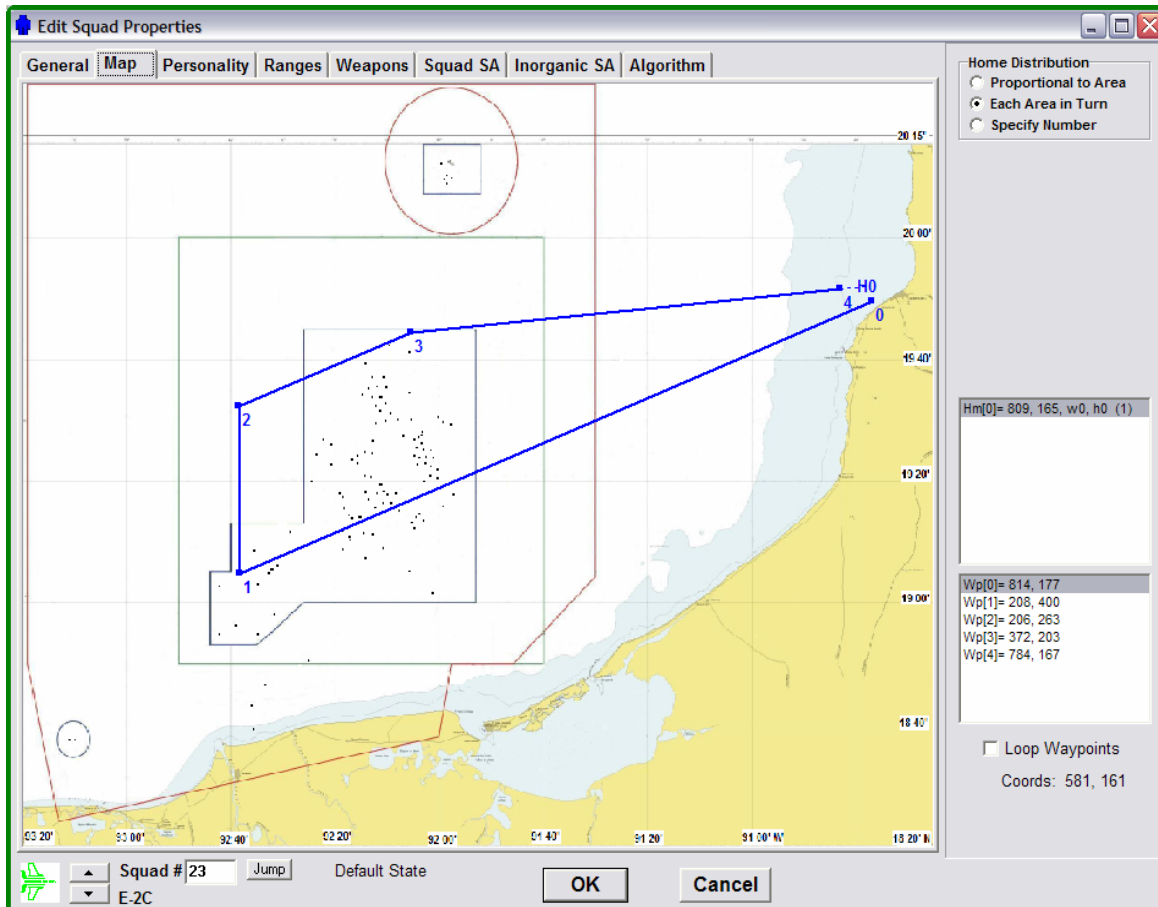
Figure 15.   Screen of the *Map* properties under the "Edit Squad Properties" menu. (best viewed in color)

The *Personality* (properties) screen is where the personality of each entity in the simulation is created. This is done basically by "weightings": each personality is described by a weighting that can be varied by a scrollbar between -100 to 100. The higher the value the greater the attraction; the more negative the value the greater the repulsion. The weighting factors can cause the entities to react to other entities, waypoints, terrain, and information on the Situational

Awareness map. One of the advantages of MANA over other similar agent-based combat models is the event-driven personality changes. Events such as an enemy contact, a squad injured or refueled by enemy can all trigger a different personality set that lasts for a user specified amount of time. Each new state allows a new, different personality for a squad.
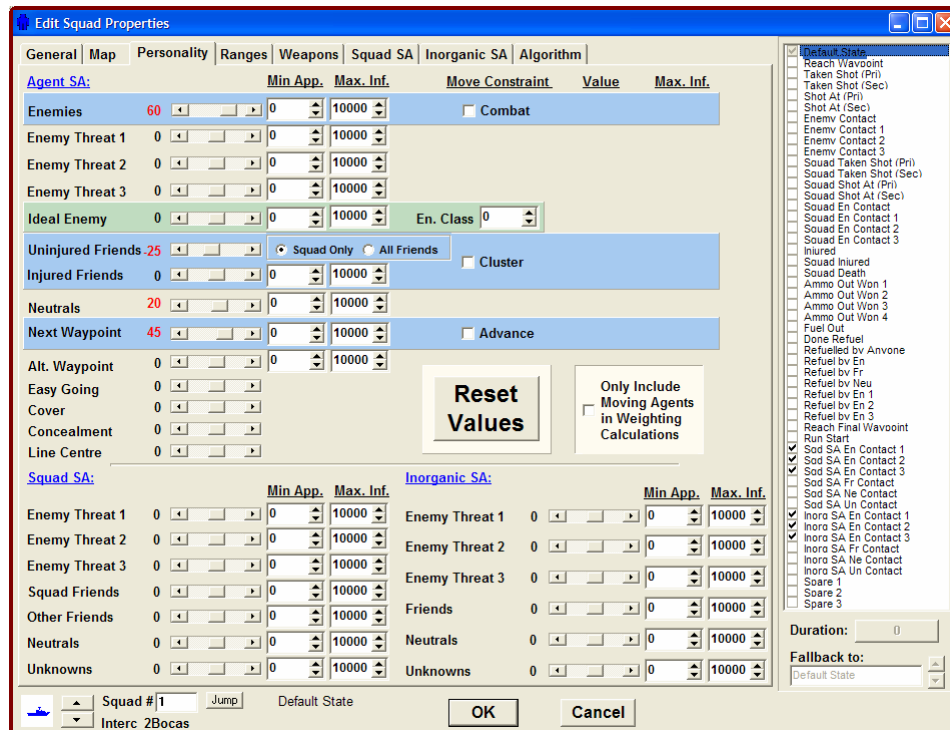
Figure 16.   Screen of the *Personality* properties under the "Edit Squad Properties" menu. (best viewed in color)

Figure 16, shows the default personality of one interceptor boat in the simulation. The personality settings are according to the location from which the information is coming. The personality screen is divided into three sections: Agent Situational Awareness (SA), which refers to the information that the agent itself has gathered; Squad SA, which refers to the shared memory map maintained by the agent's parent squad; and Inorganic SA, which refers to information shared by other squads using communications links explained later in the thesis. The red values are values that were changed from their original values. Almost all the blue agents in the simulation have the same default personality. An enemy weight of 60 means that the agent has a propensity of 60 out of 100 to go to any enemy ship that appears in its agent-situational-

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awareness. The negative value -25 for Uninjured Friends is because we do not want two or more blue squads to be together at the same time. Each squad has its own respective patrol area. Thus, when one squad goes to an enemy, the other blue agents do not have to go at the same time. That is, there is a built-in repulsion among them. A neutral propensity of 20 and Next waypoint of 45 makes it more important for a ship, say, to continue its patrol than to move to a classified neutral ship. All the other weights retain their original values.

The trigger states for all the blue agents are almost the same: Squad SA enemy 1, 2, and 3 and Inorganic SA enemy 1, 2, and 3. For each of these trigger states, there is a different personality for the agents. Figure 17 shows the different personality of the same interceptor boat in a different state. The trigger state in this example is an Inorganic SA enemy 3, which means that, when the agent is alerted by a friendly squad about an enemy threat 3, it has a propensity of 80 to go to an enemy threat 3. If there is an enemy threat 2 in the same SA area, to go toward it with a lesser propensity of 60. The negative value -25 occurs for the same reason explained previously.

Figure 17.   Screen of the *Personality* properties different of the default state under the "Edit Squad Properties" menu. (best viewed in color)

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The personality of the red agents is to go to their next waypoints (targets) with a propensity of 70 out of 100. In the default state, red agents are threat 2 and hide among the fishing boats, with the same speed as the boats in order to be concealed. The trigger states are an enemy contact and refueled by enemy 1. In case of enemy contact, when an enemy blue agent is close to them, the red agents increase to full speed to go toward their targets, because this means they have been discovered. In the case of refueled by enemy 1, it is a simple modeling trick to increase the red agents speed, because they have not been discovered by any blue agents and are entering the maritime prevention area.

For each personality's squad properties, the values of the squad property *Ranges* are dependent on the current squad state. The window shown in Figure 18 shows the ranges property of a blue agent. Here we can set the capabilities of the sensors, and the movement speed, fuel rate, concealment, threat levels, and the particular icon for each agent. This window also introduces the capabilities of each blue agent, as was explained in Chapter II.
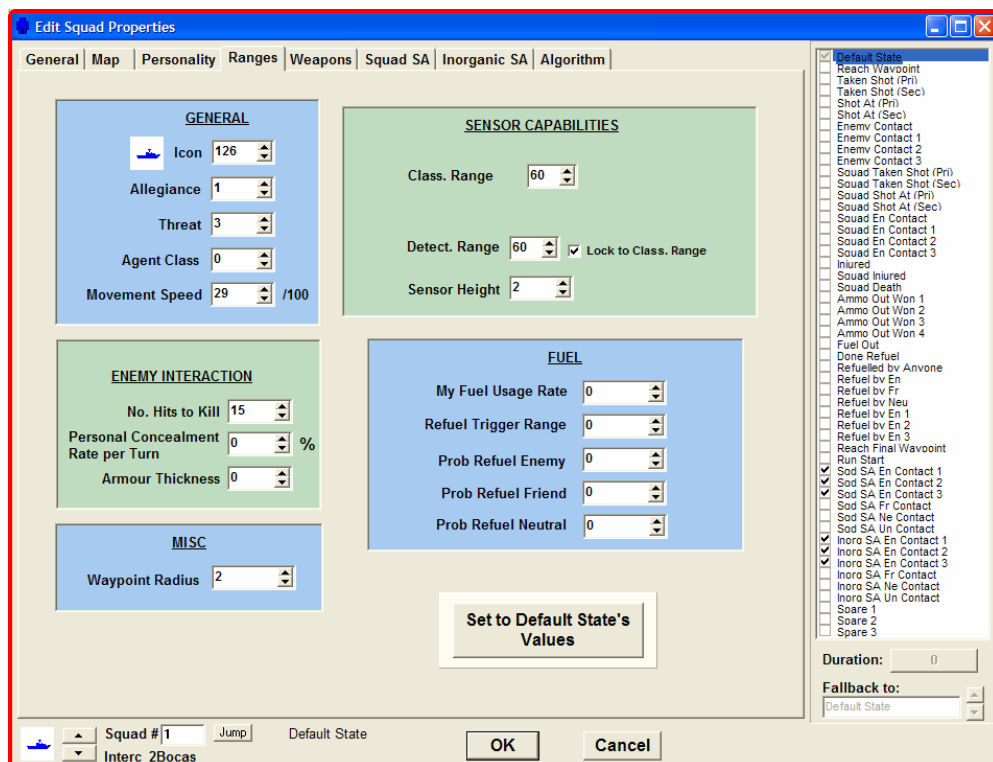
Figure 18.   Screen of the *Ranges* properties under the "Edit Squad Properties" menu. (best viewed in color)

Each squad has up to four weapons available, and most of the parameters for each weapon are able to change with a trigger state. The screen in Figure 19 shows the *Weapons* editing panel. The kinetic Energy/Agent SA was the one selected for all the blue agents, changing the Range to Shooter depending on the agent and type of weapon. In the Protect Contact Type box, we selected "to protect self, squad friends, other friends neutral and unknowns" for all the blue squads. The red squads use a high-explosive-style weapon with a short range to shooter, because they are kamikaze boats trying to explode the weapon as close as possible to one of the oil platforms.
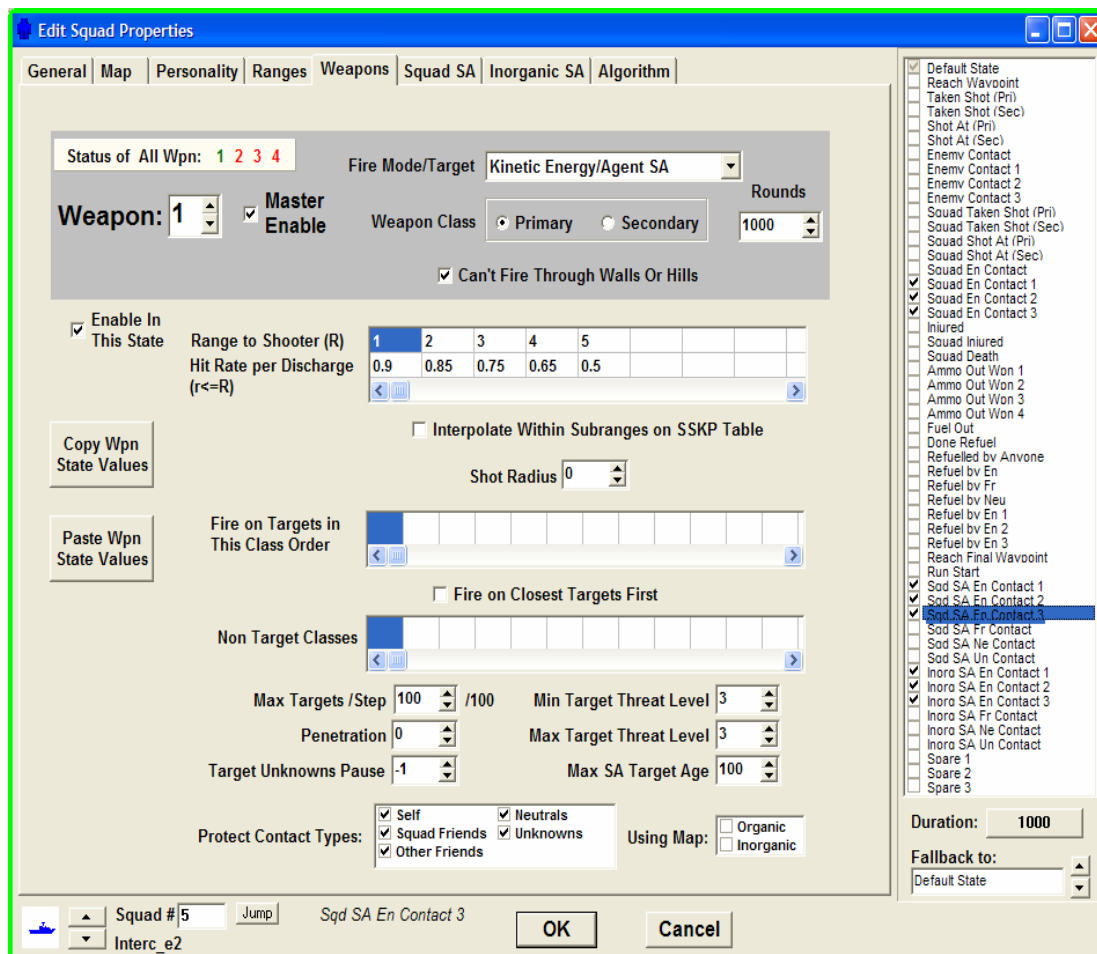
Figure 19.   Screen of the *Weapons* properties under the "Edit Squad Properties" menu. (best viewed in color)

The *Squad SA* (Figure 20) controls the flow of the situational awareness within the squad and does not vary with the trigger states; all the agents in the simulation retain their original parameters.
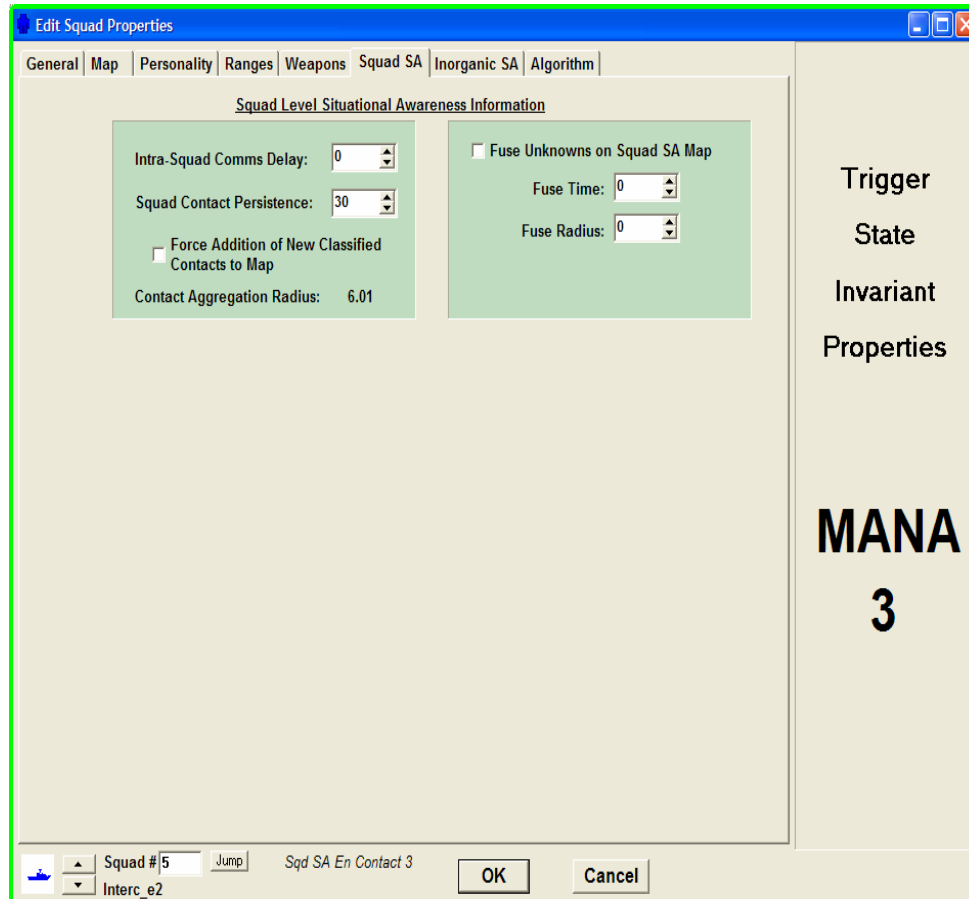
Figure 20.   Screen of the *Squad SA* properties under the "Edit Squad Properties" menu. (best viewed in color)

The *Inorganic SA* panel controls the flow of situational awareness among squads using communication links as carriers of information. The parameters of this panel do not vary with the trigger states. In the model, almost all the blue squads have communication among them; Figure 21 shows a screen where a given squad has communication with the number of squads shown in the table.

The parameters changed are "Reliability," with 100%, and "Delivery," with guarantee delivered in all the cases. The final option indicates the type of contact information to pass over the link.
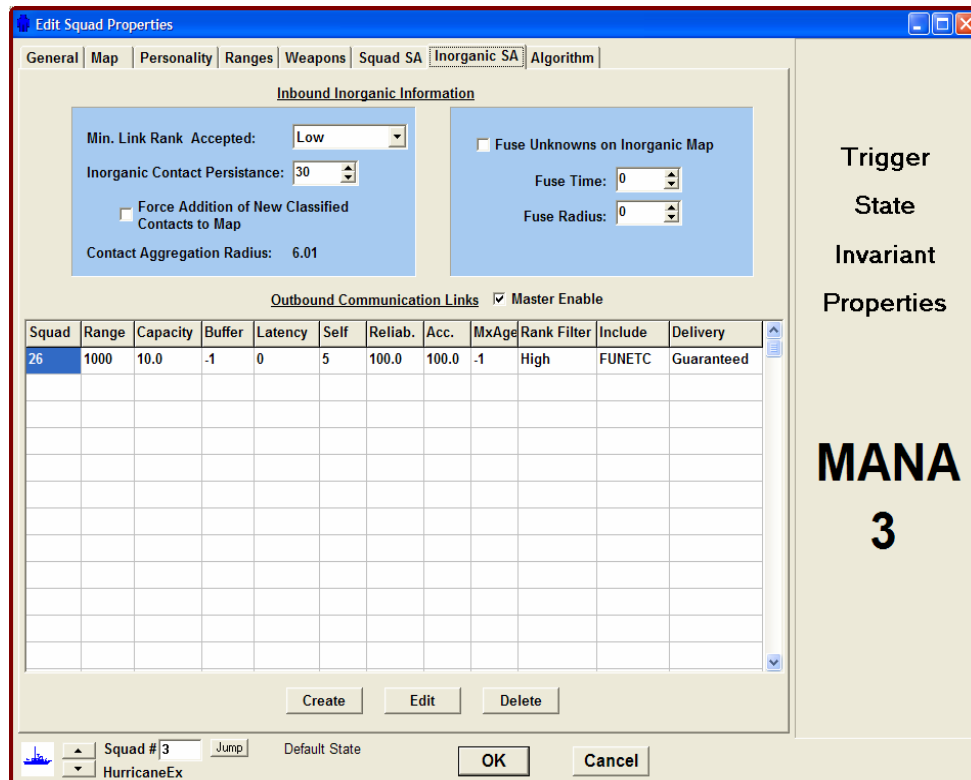
Figure 21.   Screen of the *Inorganic SA* properties under the "Edit Squad Properties" menu. (best viewed in color)

Table 9 shows the contact types to pass as messages on the link. In the model, all the blue agents use the "FUNETC" option, except the aircraft to which they also have to send their position.

S	Share positions of own agents
F	Share details of friendly contacts
U	Share details of unclassified contacts
N	Share details of neutral contacts
E	Share details of enemy contacts
T	Share Squad's Local Situational Awareness
C	Share Inorganic Situational Awareness

Table 9.   Contact types to send on link.

The *Algorithm* panel (Figure 22) is used to change some of the movement algorithm options. All the agents in the model, except the aircraft, use the Stephan Algorithm (default) and the aircrafts use the Path Following algorithm; this is done because this algorithm is better for modeling the motion of aircrafts on maritime patrol.
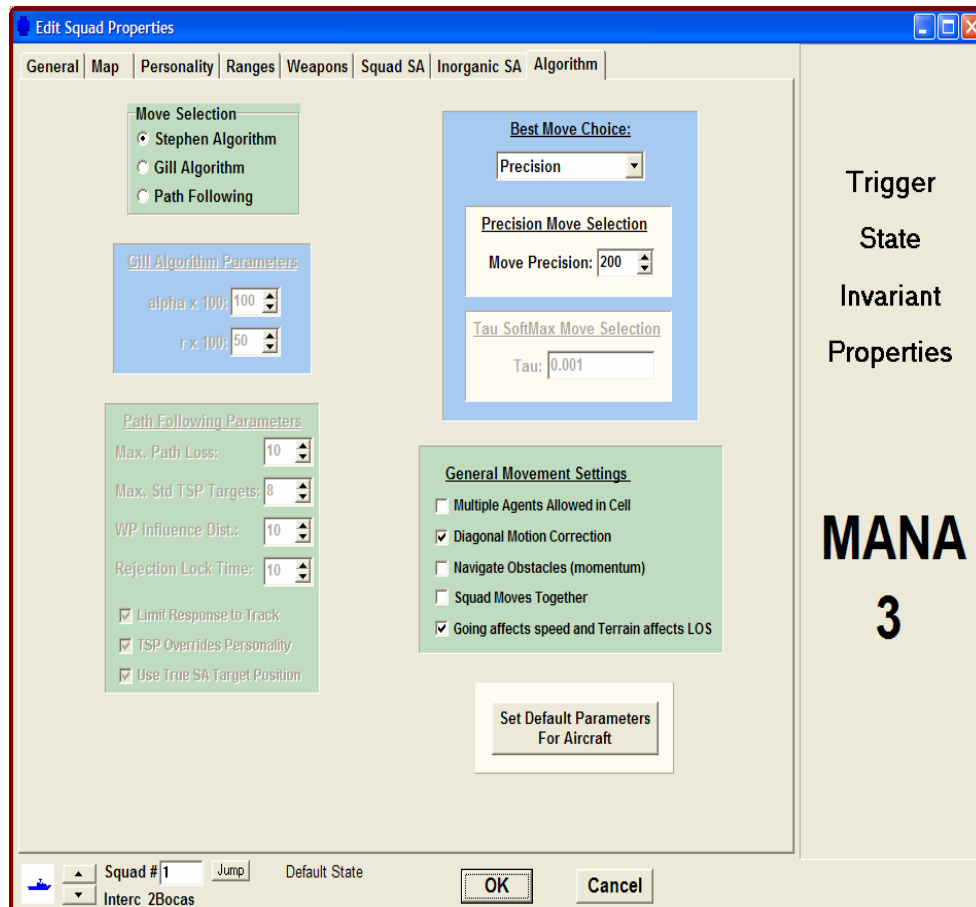
Figure 22. Screen of the Movement *Algorithm* parameters under the "Edit Squad Properties" menu. (best viewed in color)

3. Measure of Effectiveness in MANA

There is a Data Output Menu in MANA, which has options for recording extra information in addition to the standard MultiRun file. The output options available for this version are: record step-by-step data, record casualty-location data, record agent-state data, record detections, record Multi-Contact detections, and record positions. The MultiRun standard result file of this version of MANA contains different measures: for example, for each run, the random seed used,

the number of casualties for allegiance one and two, whether or not allegiance one or two reach final waypoints, and the casualties of each squad. For this study, additional output files are not necessary to get the measure of effectiveness explained in chapter two. It is only necessary to get the mean of the number of times the targets (i.e., critical petroleum facilities) are killed in each run, and afterwards, to calculate in a spreadsheet the probability that at least one target is destroyed per run.

IV.   DESIGN OF EXPERIMENTS

Multiple scenarios could develop in the Campeche Sound, depending on the navy's resources in the area and the enemy force's capabilities. Some of the navy resources in the area are fixed: they never change. But there are others that sometimes are not the same. This occurs because the navy has more than one operation to perform. Another reason is the maintenance plan of the units. Nevertheless, if a certain type unit is not able to be there, it will be replaced by an equal type unit or by another type unit with similar characteristics. This chapter explains the two main factor classes involved in the experiments, controllable factors and noise factors, and the robust design that best explores the parameters of the model.

A.   MEXICAN NAVY SCENARIOS - CONTROLLABLE FACTORS

For the purpose of this study, the factors that the Mexican Navy can control include all the different combinations of the actual resources in the Campeche Sound. It may seem obvious that if the number of the navy resources in the area were augmented, then the probability that an enemy would destroy at least one oil platform would be lessened. Nevertheless, this study tries to find the best combination of resources at the lowest cost. The controllable factors are the different combinations possible in the area by interchanging the various elements and practices of the overall navy force:

- Presence of the HAWKEYE AEW.

- Presence of the AVIOCAR MPA.

- Aerial patrol by aircraft, type REDIGO, or helicopter, MI-17.

- Patrol area of a HURACAN ship.

- Number of additional POLARIS interceptor boats in the area (0-2).

Using a full factorial design (Law and Kelton, 2000) is an effective way to evaluate the possible combinations of the naval resources in the area. The presence of the various units is expressed as the binary values 0 and 1. Zero, if a certain unit is not present in the simulation and one otherwise. In the beginning, we considered all the possible combinations of the resources, but a preliminary analysis showed that the factor of an aerial patrol by an aircraft type REDIGO or a helicopter MI-17 was not relevant in the model. This does not mean that they are not necessary in the simulation. It means that, with either of those aerial types, the result in the simulation is the same. Appendix one shows the data analysis of this preliminary finding. Table 10 shows the final, most important combinations of the naval factors.

HAWKEYE	AVIOCAR	HURACAN Exclusion area wo/ He	HURACAN Exclusion w/He	HURACAN Maritime Prevention area wo/He	HURACAN Maritime Prevention area w/He
0	0	0	0	0	0
0	0	0	0	1	1
0	0	0	0	1	0
0	0	1	1	0	0
0	0	1	0	0	0
0	1	0	0	0	0
0	1	0	0	1	1
0	1	0	0	1	0
0	1	1	1	0	0
0	1	1	0	0	0
1	0	0	0	0	0
1	0	0	0	1	1
1	0	0	0	1	0
1	0	1	1	0	0
1	0	1	0	0	0
1	1	0	0	0	0
1	1	0	0	1	1
1	1	0	0	1	0
1	1	1	1	0	0
1	1	1	0	0	0

Table 10.   Full factorial design of the possible scenarios of the navy resources in the area, with only the controllable factors.

In addition, the study analyzes the effect on the output of incorporating one or two additional intercepting boats in the area. Therefore, the total number of possible scenarios with the controllable factors is 60 (20 x 3).

B.   ENEMY CAPABILITIES - NOISE FACTORS

There are some factors that are not controllable by the navy, for instance, the number of terrorist boats, speed of the boats, types of boats, tactics, weather, number of fishing boats entering the forbidden area, etc. For this study, we considered only three uncontrollable factors: number of terrorist boats, the speed of those boats, and the number of fishing ships entering the forbidden area. In this study the enemy has only one tactic, because the tactic considered for this model is a worst-case example. A different tactic would add more reaction time for the navy units in the area.

Latin Hypercubes and Nearly Orthogonal Latin Hypercubes provide a very good, all-purpose design, particularly when the factors used are quantitative. The reason this is so is due to their efficiency, space-filling ability (if we look at any pair of factors, we find a variety of combinations), design flexibility, and analysis flexibility. The Latin Hypercubes are efficient designs for examining the impact of simultaneously changing the specified factor values (Kleijnen, Sanchez, Lucas, and Cioppa, 2005). The Orthogonal Latin Hypercubes (OLH) design was chosen for its excellent space-filling properties, the resulting lack of correlation between factors' inputs, and the ability to identify nonlinear relationships (Cioppa, 2002). OLH can be used to design an experiment evaluation with seven factors, at seventeen levels each. A NOLH design with almost the same properties, but slightly more correlation between factors, can be used to evaluate from eight to twenty-two factors, at up to 129 levels. Therefore, for the noise-factor design we used an Orthogonal Latin Hypercube design with three factors, requiring only 17 runs. The construction of the OLH design was done in the Microsoft Excel spreadsheet created by Professor Susan Sanchez (SEED Lab, NPS, 2005). An example of the design in that spreadsheet is shown in Figure 23. The user must first choose the appropriate worksheet, depending on the number of factors, and

then fill out the low level and the high level and name of each factor. The spreadsheet will create the design in the light-yellow entries. Table 11 shows the low and high levels of the three noise factors used in the simulation.

Factor	Low real level	Low level in MANA	High real level	High level in MANA
Number of terrorist boats	1		3	
Speed terrorist boats	20 knots	29	45 knots	64
Number fishing ships in the forbidden area	0		5	

Table 11. Low and high levels of the controllable factors.

Figure 23. Screen of the NOLH spreadsheet design. (best viewed in color)

Table 12 shows the correlation matrix of the noise factors in the OLH design. The correlation of the number of terrorist boats with the speed of the terrorist boats is 0.11. This is because the factor of the number of terrorist boats has only three levels and therefore there is some rounding.

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	Number terrorists	Speed of terrorist	Fishing boats
Number terrorists	1.00000000	0.11685718	0.07753364
Speed of terrorist	0.11685718	1.00000000	0.05068842
Fishing boats	0.07753364	0.05068842	1.00000000

Table 12.   Correlation matrix of the noise factor in the OLH design.

The pairwise projections of the 17-runs, three-factor orthogonal hypercube of the noise factors is shown in Figure 24. This shows the near orthogonality and space-filling behavior of the design.
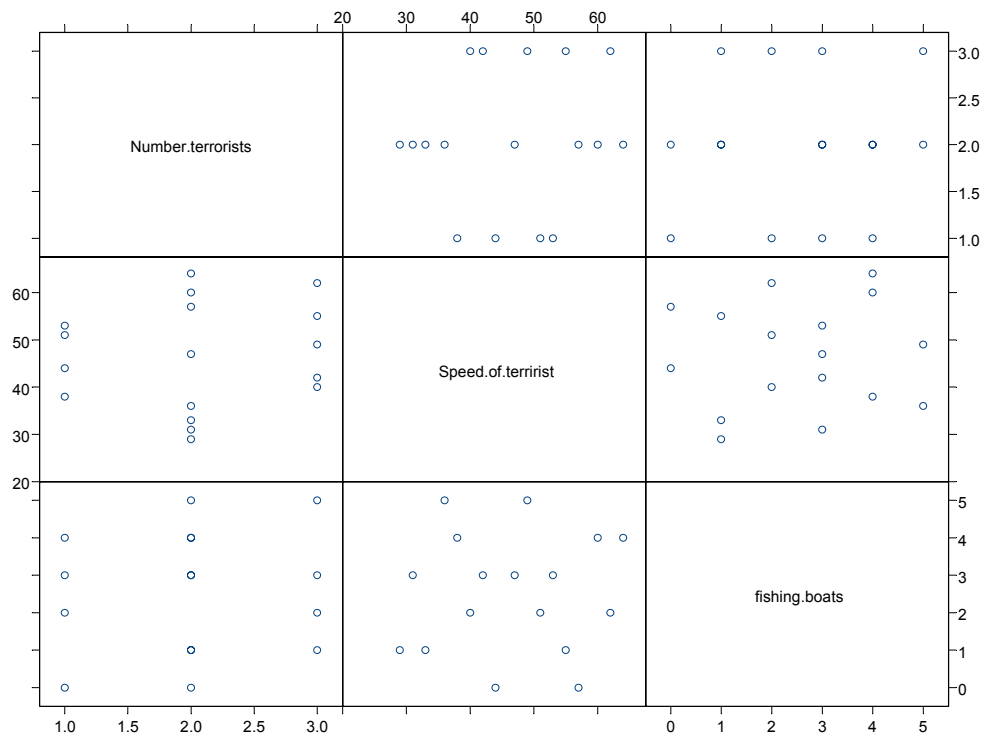
Figure 24.   Screen of the pairwise projections of the 3 factors in the OLH design.

C.   FINAL EXPERIMENTAL FACTORS

The final design includes the twenty design points of the possible scenarios of the controllable factors, crossed with the seventeen design points of the OLH design of the uncontrollable factors, and finally crossed with the single

controllable factor with three levels from the effect of using zero, one or two interceptors in the area. The result is 20 times 17 times 3 = 1,020 design points. Finally, the 1,020 design points are sent to the Maui High Performance Computer Center (MHPCC), to run fifty iterations each, with a total of 51,000 MANA runs of the scenario. Figure 25 shows a scheme of the final experimental design.

$$
\begin{matrix}
\text{Scenario's} \\
\text{Controllable} \\
\text{Factors}
\end{matrix}
\qquad
\begin{matrix}
\text{Single} \\
\text{Controllable} \\
\text{Factor} \\
\text{3 levels}
\end{matrix}
\qquad\qquad
\begin{matrix}
\text{Uncontrollable} \\
\text{Factors}
\end{matrix}
$$

$$
\begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ . \\ . \\ . \\ 20 \end{bmatrix}
\times
\begin{matrix} \text{additional} \\ \text{interceptors} \end{matrix}
\begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}
\times
\begin{bmatrix}
\#\,enemy\,boats & Speed\,of\,boats & \#\,fishing\,ships \\
total\;17 & total\;17 & total\;17 \\
from\,1\,to\,3 & from\,20\,to\,45 & from\,0\,to\,5
\end{bmatrix}
= 1020
$$

Figure 25.   Scheme of the representation of the final experimental design.

This experimental design took a little more than twenty-four hours to run at the MHPCC, a time that is not comparable to the time it would take to run the same scenario in the traditional full factorial design. In the full factorial design it would be necessary to have at least 60,000 runs, which is almost sixty times more runs than the experimental design. Therefore, the time to complete the same scenario would take at least sixty days to get the same results.

V.   DATA ANALYSIS

This chapter explains the initial assessment of the data followed by a detailed analysis of the data. The analysis includes the critical factors in the model, a linear regression model with all the main effects and the two-way interactions of all the factors, and the linear regression model with only the controllable factors (Mexican Navy resources). Finally, we explain in detail all the analysis findings in the model, not only in statistical terms, but also in terms of what this means in real life in each particular scenario.

A.   INITIAL ASSESSMENT OF THE DATA

When the experimental design is processed and completed at the Maui High Performance Computing Center (MHPCC), a comma-separated values (CSV) text file is generated by the MHPCC cluster with all the inputs of the experimental design and the desired MOEs. Next, thanks to the data-farming environment output, the desired information is extracted from the simulation model. The CSV file, in this case, has all of the 1,020 input combinations explained in the previous chapter, along with data such as blue casualties, red casualties, blue injured, and red injured, among others. For this particular MOE (explained in chapter two), we need the number of targets killed (i.e., the critical platforms). The probability that an individual target has been destroyed is estimated by simply adding the times a target is killed in a particular scenario and dividing by the number of iterations (fifty). Then, having three targets, we calculate the MOE (i.e., the probability that at least one platform is destroyed out of the three) for each scenario. The JMP Statistical Discovery Software, version 5.1.2, was used as a primary tool for data processing and data analysis. Figure 26 shows the distribution of the probability to destroy each platform and the probability to destroy at least one platform. A probability of kill 1, 2, or 3 means the probability that the enemy destroyed critical platform number 1, 2, or 3 respectively. We should mention that, if there is only one terrorist boat, it will attack critical platform number 1; if there are two boats, one will attack separate

critical platform number 1, and the other will attack platform number 2; and, finally, if there are 3 boats, each of them will attack a different critical platform in the model. The probability of kill at least one, refers to the probability that any of the terrorist boats destroys successfully at least one of the critical platforms. Over all the scenarios the terrorist are successful 10.3 percent of the time.
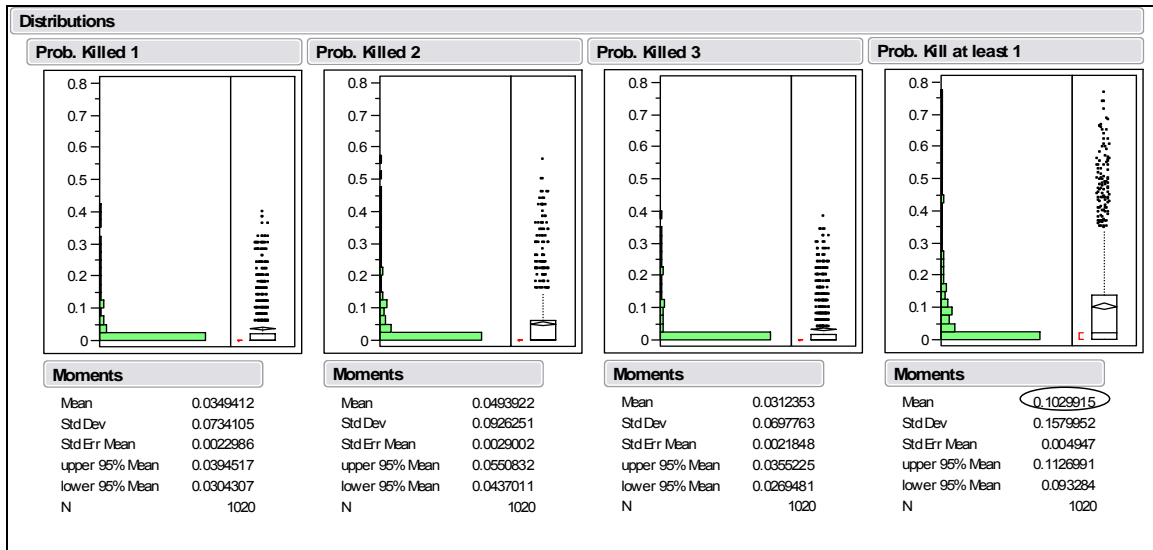
Figure 26.   Distribution of the probability of the enemy destroying each of the critical platforms and the probability of the enemy destroying at least one of them. (best viewed in color)

B.   CRITICAL FACTORS IN THE FULL MODEL

This section identifies the critical factors that, in general, affect all the scenarios. It starts with a partition tree of the data, followed by a one-way analysis of the contribution of each individual factor in the model. In the one-way analysis, because of the absence of normality, a non-parametric test is used to test the null hypothesis in the tests.

1.   Classification Tree

This feature is used to fit classification and regression trees. The partition algorithm recursively partitions the data according to a relationship between X and Y values, creating a partition tree (JMP version 5.1.2, 2004). This technique is usually used in data mining, because:

- It is good for exploring relationships without having a good prior model,
- It handles large problems easily, and
- The results are very interpretable.

The response column (Y's) in this case is the probability that at least one platform is destroyed. The factors columns (X's) are all the resources of the navy in the scenarios and all the noise factors in the model.
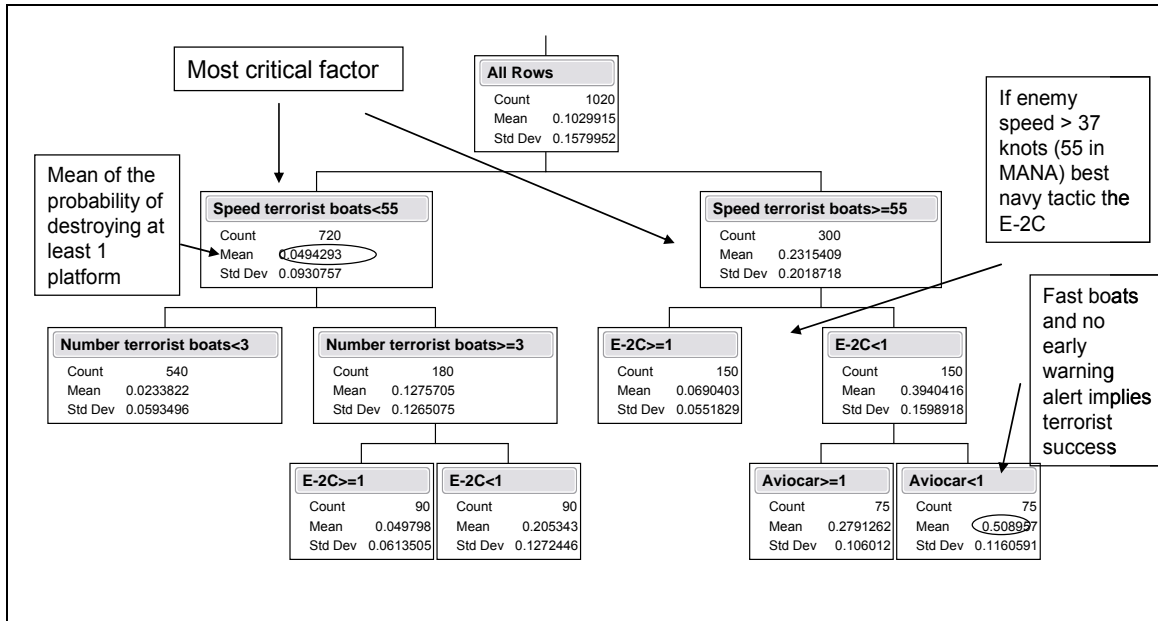
Figure 27.   Partition tree feature in JMP version 5.1.2 including all the factors in the model.

The partition tree feature in JMP version 5.1.2 is shown in Figure 27. The goal of this analysis if to investigate which factors affect the response variable, which in this case is the probability to destroy at least one platform in all the scenarios. The first split shows the most important factor, which in this case is the speed of the terrorist boats. This means that there is a significant effect on the response when the speed of the terrorist boats is greater than 38 knots (55 in MANA). The second split splits each of the groups previously generated in the first split, and so on. For instance, if the speed of the terrorist boats is greater than 38 knots, it is essential to have the HAWKEYE present in the scenarios to decrease the probability, if this was not possible, to have the maritime patrol aircraft in the area.

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2. One-way Analysis of Critical Factors

The one-way analysis of means is the attribution and test that part of the total variability in a response is due to the difference in mean responses among the factor groups.

a. E-2C HAWKEYE AEW

Figure 28 shows the effect of the contribution of the E-2C HAWKEYE AEW aircraft in the scenarios. The two boxplots are the vertical distribution of the response points for each factor of X (E-2C HAWKEYE AEW). In this case the factors are zero if the HAWKEYE AEW is not present in the scenario and one otherwise. The boxplots show clearly that the means and variances of the probability of kill at least one platform are different. The mean of not having the HAWKEYE AEW in the scenario is 0.17, while the mean of having the HAWKEYE AEW in the scenario is 0.03. A t-test t is not necessary to show that the means are different.

Oneway Analysis of Prob. Kill at least 1 By E-2C

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0	0	0	0.11604	0.301036	0.482932	0.76592
1	0	0	0	0	0.04	0.0976	0.308512

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	510	0.175831	0.191894	0.00850	0.15914	0.19253
1	510	0.030152	0.050186	0.00222	0.02579	0.03452
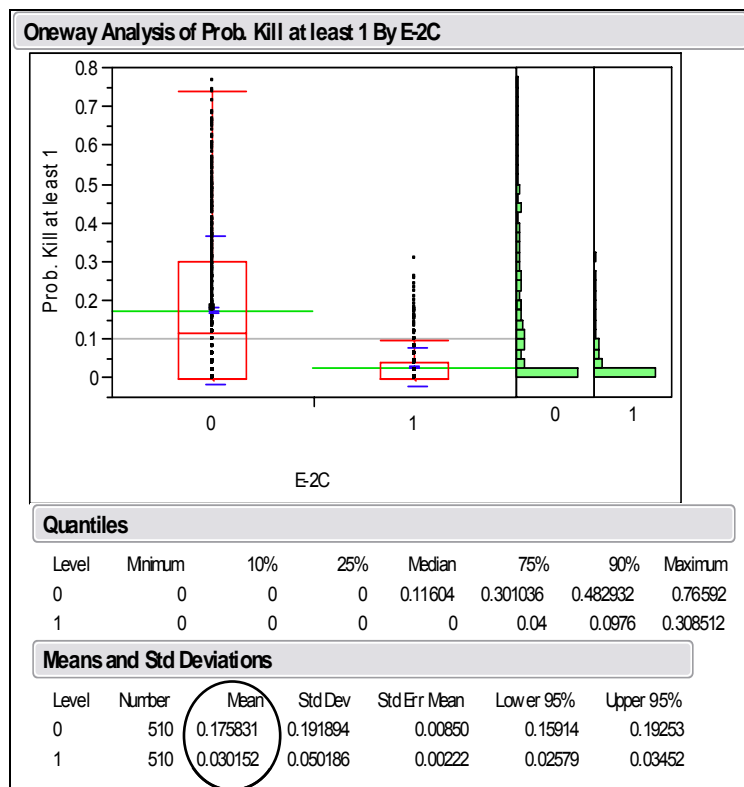
Figure 28. One-way analysis of means of the probability of destroying at least one platform with the HAWKEYE AEW aircraft in the model.

b.   C-212 AVIOCAR MPA

The AVIOCAR MPA has almost the same effect in the model as the HAWKEYE AEW. Figure 29 shows the one-way analysis of the effect of the AVIOCAR MPA in the scenarios. The absence of normality in the data led to a decision to use the non-parametric Wilcoxon signed-rank (rank-sum) test to examine the hypothesis. The null hypothesis in the test is that the means are equal. The *p*-values are the 'Prob>|Z| .0002' entry in Figure 29 and the 'Prob>ChSq .002.' This is because we have only a two-level factor (0 and 1). Given that the value of alpha is .05 ($\alpha = 0.05$), the null hypothesis is false ($\alpha >$ Prob>|Z|). With this test we can conclude that there is a difference in the means for the probability to destroy at least one platform when the AVIOCAR MPA is present in the area.

Oneway Analysis of Prob. Kill at least 1 By Aviocar

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0	0	0	0.0396	0.173114	0.480302	0.76592
1	0	0	0	0.02	0.1168	0.247024	0.4852

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	510	0.131683	0.190393	0.00843	0.11512	0.14825
1	510	0.074300	0.109885	0.00487	0.06474	0.08386

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
0	510	277074.5	543.283	3.688
1	510	243635.5	477.717	-3.688

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
243635.5	-3.68755	0.0002

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
13.5989	1	0.0002

P-values

Figure 29.   One-way analysis of means of the probability of destroying at least one platform with the AVIOCAR MPA in the model.

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c.   Patrolling Area of the HURACAN Ship

The simulation tests the two possible patrolling areas of the HURACAN ship: the exclusion area and the maritime prevention area. In this case, the one-way analysis considers the two patrol areas both with and without the shipborne helicopter on the ship. The blue line connects the means of the five situations. Table 13 shows the four different possible patrol areas of the HURACAN ship, both with and without the shipborne helicopter, and one additional scenario just to check the effect on the probability to destroy at least one platform without the HURACAN ship in the model.

Number	Area patrolling
0	Effect of no HURACAN ship in the model
1	Exclusion area
2	Exclusion area with shipborne helicopter
3	Maritime prevention area
4	Maritime prevention area with shipborne helicopter

Table 13.   Possible patrol areas of the HURACAN ship in the model.

Figure 30 shows the means of the probability of destroying at least one platform for all five levels in Table 13. In all cases, the null hypothesis is that the means are equal. Since the p-value 'Prob>ChSq' is 0.0185, the null hypothesis is false with an alpha value (significance level) of 0.05 ($\alpha = 0.05$). The non-parametric Median test (k-sample median) in the JMP 5.1.2 entry in Figure 30 also shows that the "Mean-Mean0/Std0' of both patrol areas with the shipborne helicopter (2 and 4) are negative, which means that they are different from the other three patrol areas. Therefore, we can conclude that the patrol area of the HURACAN ship is a significant factor in the model only when the HURACAN has the shipborne helicopter. This makes sense because the shipborne helicopter enhances the classification range and the capability of reaction of the ship.
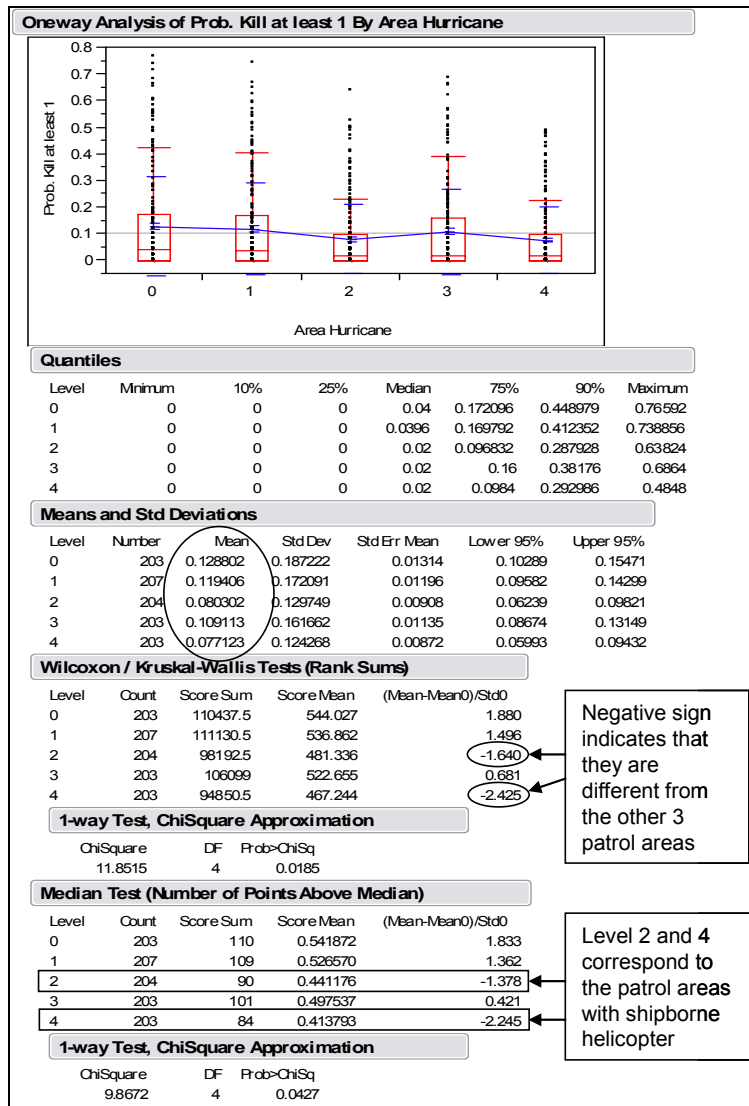
Figure 30.   One-way analysis of the means of the probability of destroying at least one platform by the patrolling of the area with the HURACAN-class Missile Ship.

d.   Additional Interceptor Boats class POLARIS in the Scenario

The twenty different scenarios are tested with the possible addition of 0, 1, or 2 POLARIS interceptor boats in the scenarios. Figure 31 shows the one-way analysis of the probability to destroy at least one platform with the addition of 0, 1, or 2 interceptor fast boats in the area. At first glance, we see that there is no difference in the means. The *p*-value 'Prob>ChSq' is 0.6647 with an alpha value of 0.05, which means that we do not reject the null hypothesis that

the means are equal. Even though the null hypothesis test is that they are equal, the Wilcoxon/Kruskal-Wallis test indicates that the probability of destroying at least one platform, when one or two interceptors are added in the scenarios, is slightly different than with no additional interceptors. We can conclude that there is no difference when adding one or two additional interceptors in the scenarios, but there is a difference between adding and not adding. This is because, when two interceptor fast boats are added, one of them covers a different area, where the terrorist boats are. So we can conclude that there is a difference from adding one interceptor boat in the model only if its covering area is involved when a terrorist boat attacks.

Oneway Analysis of Prob. Kill at least 1 By additional Interceptors

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0	0	0	0.0396	0.14996	0.366976	0.738856
1	0	0	0	0.02	0.134824	0.31191	0.71272
2	0	0	0	0.02	0.1352	0.375533	0.76592

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	340	0.110330	0.164504	0.00892	0.09278	0.12788
1	340	0.096699	0.149445	0.00810	0.08076	0.11264
2	340	0.101946	0.159827	0.00867	0.08490	0.11900

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
0	340	177430.5	521.854	0.903
1	340	170982	502.888	-0.605
2	340	172297.5	506.757	-0.298

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
0.8472	2	0.6547

P-value greater than 0.05 value of alpha

Figure 31.   One-way analysis of the means, with additional POLARIS interceptor boats, of the probability of destroying at least one platform.

e. Number and Speed of Terrorist Boats

As we expected, increasing the number and speed of the terrorist boats increases the probability to destroy at least one platform. A non-parametric test to see if the means are different is not necessary. Figure 32 shows that the probability to destroy at least one platform is increased as the number and speed of the terrorist boats is incremented. With one boat the terrorist are almost never successful.
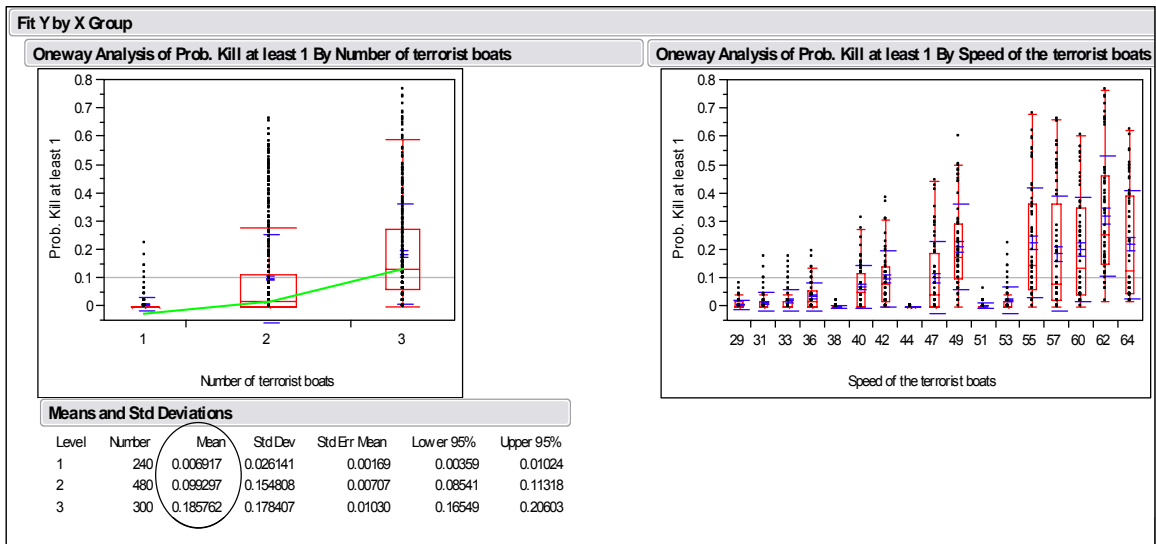
Figure 32. One-way analysis of the means, by number and speed of the terrorist boats, of the probability of destroying at least one platform.

f. Fishing Boats Entering the Forbidden Area During a Terrorist Attack

In the model an excursion of fishing ships is simulated entering the maritime prevention area during an attack by terrorist boats. This is because, whenever an unknown ship enters the maritime prevention area, at least one navy unit has to recognize this ship and "push it away" from the area. This would make the unit unable to go to the real target during an incursion of terrorist boats. Figure 33 shows the repercussion in the response variable when zero to five fishing boats enter the maritime prevention area during an attack by terrorist boats. The *p*-value in the ChiSquare approximation 'Prob>ChSq' is 0.001, which means that the null hypothesis that the means are equal is rejected. The

Wilcoxon/Kruskal-Walls test in Figure 33 indicates that the means when there is zero, one or three fishing ships are equal. This is because the data of the number of fishing ships entering the forbidden area and the number and speed of the terrorist boats are slightly correlated.

Oneway Analysis of Prob. Kill at least 1 By Number fishing ships entering forbidden area

Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
0	0	0	0	0	0.0796	0.4376	0.66
1	0	0	0	0.02	0.092324	0.347674	0.680128
2	0	0	0	0.049204	0.171448	0.434058	0.76592
3	0	0	0	0.02	0.08	0.196086	0.4424
4	0	0	0	0.04	0.2608	0.4666	0.622
5	0	0	0.005	0.0784	0.1792	0.336851	0.59752

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
0	120	0.093230	0.173077	0.01580	0.06195	0.12451
1	180	0.085274	0.152105	0.01134	0.06290	0.10765
2	180	0.131518	0.187719	0.01399	0.10391	0.15913
3	240	0.060065	0.093921	0.00606	0.04812	0.07201
4	180	0.142160	0.182311	0.01359	0.11535	0.16897
5	120	0.123641	0.141461	0.01291	0.09807	0.14921

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
0	120	52966.5	441.387	-2.839
1	180	83842.5	465.792	-2.328
2	180	98701.5	548.342	1.970
3	240	109315	455.479	-3.433
4	180	103624	575.689	3.394
5	120	72260.5	602.171	3.765

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
45.7823	5	<.0001

Figure 33.   One-way analysis of the probability of destroying at least one platform as a function of the number of fishing ships entering the prevention area during a terrorist attack.

Table 14 shows the values of the NOLH design of the number of terrorist boats, the speed of the terrorist boats, and the number of fishing boats entering the forbidden area. The values highlighted are the values when there are three fishing boats entering the maritime prevention area. When there are three fishing boats, the maximum speed of the terrorist boats is 37 knots (53 in MANA), but there is only one terrorist boat, so the probability to destroy at least one platform is small. Therefore in this case, the probability of destroying at least

one platform when there are three fishing boats should be small. This is because, when the speed of the terrorist boats is slightly greater, there are only one or two terrorist boats. When there are three attackers, their speed is sufficiently slow that they can be interdicted by the Navy units. Excluding the mean value of three fishing boats, we can conclude that there is a critical effect on the probability of destroying at least one platform when there are more than two fishing boats entering the maritime prevention area during a terrorist boat attack.

	number	speed	fishing
low level	1	29	0
high level	3	64	5
decimals	0	0	0
factor name	number terrorist	speed terrorist	fishing ships
	2	64	4
	1	38	4
	1	44	0
	1	51	2
	3	62	2
	3	40	2
	2	36	5
	2	60	4
	2	47	3
	2	29	1
	3	55	1
	3	49	5
	3	42	3
	2	31	3
	1	53	3
	2	57	0
	2	33	1

Table 14.   NOLH design of the number of terrorist boats, speed of the terrorist boats, and number of fishing boats entering forbidden area.

3.   Regression

A stepwise regression was performed to examine the relationship of the controllable factors and the noise factors. Stepwise regression is a method of selecting factors with significant effects for a regression model. The purpose of a regression in this case is to find a mathematical equation that fits the data output in the simulation. The stepwise regression produced in JMP 5.1.2 is shown in Figure 34. The mathematical equation shown provides an explanation of the response (the probability of destroying at least one platform), based on the

significant factors that result in a minimal amount of error. The final model in Figure 34 is the one that better provides parameter estimates for the significant factors that result in the most preferred *R*-squared value, 87.7%, and an adjusted *R*-Squared value of 86.9%. By definition, "R-Squared" is the proportion of variability in the response explained by the regressor *X* (Montgomery, Peck and Vining, 2001). Values of R-Squared that are close to 1 imply that most of the variability in the response is explained by the regression model.
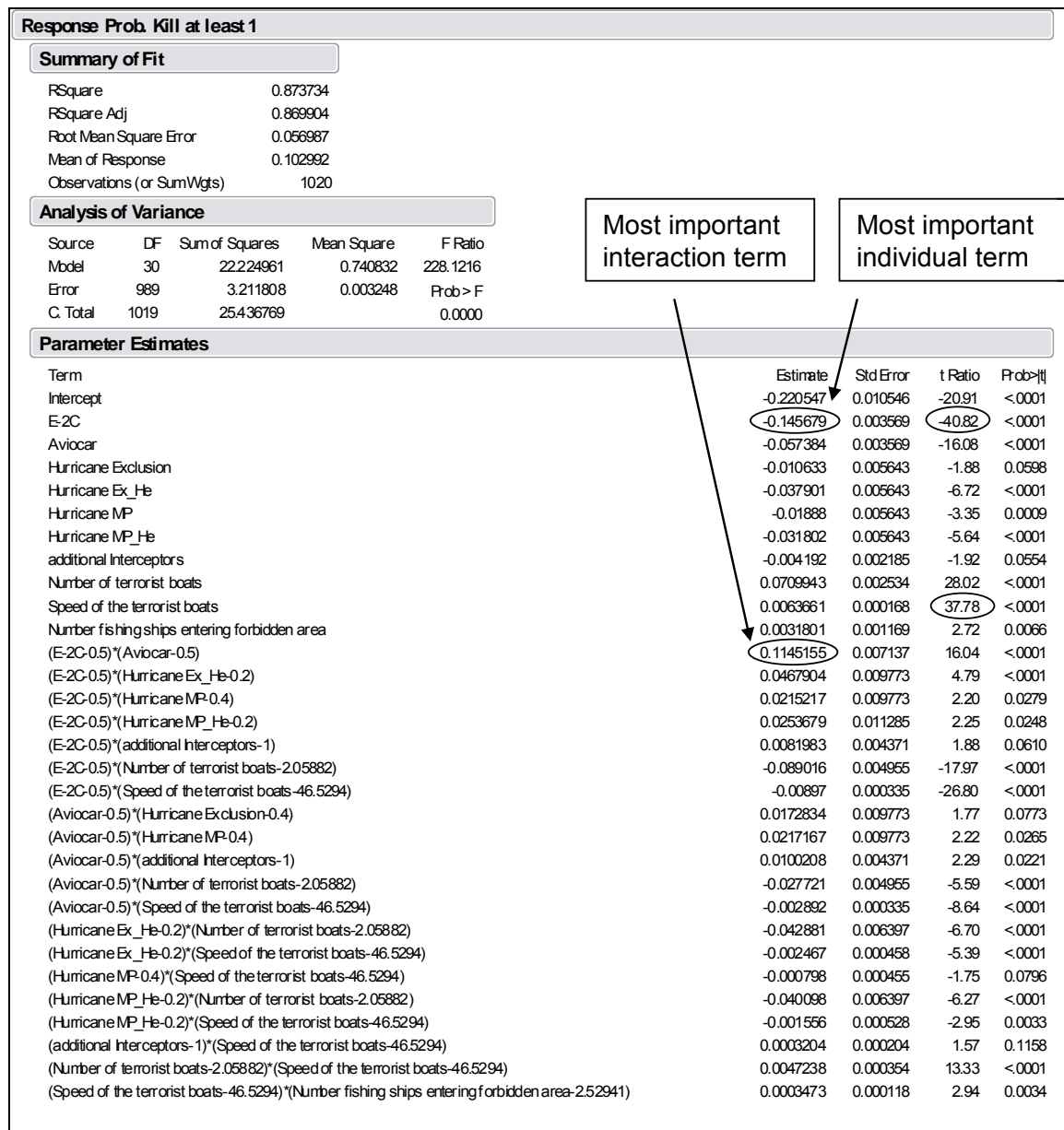

Figure 34.   Regression model with all the factors involved in the scenarios.

The third column of the right side of Figure 34 contains *t*-Ratio information. The *t*-Ratio is the ratio of the value estimated by the model formula to its standard error. A *t*-Ratio greater than 2 (in absolute value) corresponds to a significance of less 5%. (Sall et al., 2005) The absolute magnitude of the *t*-Ratio indicates the relative influence a factor has on the outcome of the probability of destroying at least one platform. The "**40.82**" for "E-2C" is the largest value in the table and thus has the most statistical significance in explaining the probability of destroying at least one platform. The negative sign indicates that there exists a negative correlated relationship (i.e., as "E-2C HAWKEYE AEW" is not present in the model, the probability of destroying at least one platform value produced in the simulation increases). This is contrasted with the second highest magnitude value of "**37.78**" for "Speed of the terrorist boats." However, in the case of "Speed of the terrorist boats," the relationship is positive correlated (i.e., as "Speed of the terrorist boats increases, the probability of destroying at least one platform also increases). Inspection of the remaining values yields an understanding of how the factors influence the probability of destroying at least one platform relative to one another.

This model makes sense. As all the Navy resources are in the model, the probability of destroying at least one platform decreases. Conversely, as the number of terrorist boats, speed of the terrorist boats, and fishing ships entering forbidden area, the probability of destroying at least one platform increases. The interaction terms indicate the significant relationships between one factor and another. The most important significant interactions terms in the model are going to be explained later in this chapter.

We plot the probability of destroying at least one platform against the predicted probability, and also the residuals against the predicted probability, to destroy at least one platform. Figure 35, left side, displays the actual vs. the predicted probability of destroying at least one platform. From the actual vs. predicted probability of destroying at least one platform plot, we can see a positive slope, indicating that the actual and the predicted probability of destroying at least one platform are in general agreement. To check the

assumption of normality for the residuals, we plotted the residuals against the predicted probability of destroying at least one platform, displayed in Figure 35, right side. In this plot, we want the residuals to have a mean of zero, constant variance and identically distributed. The plot looks good except, in the marked ellipse, there is a trend in the data when the predicted probability to destroy at least one platform is -0.15 to 0.15. This is because almost all the controllable factors are binary variables (zero and one) and the noise factors, excepting the speed of the terrorist boats, have only a few levels (3 and 5), and also because the probability of kill at least one platform can never be less than zero.
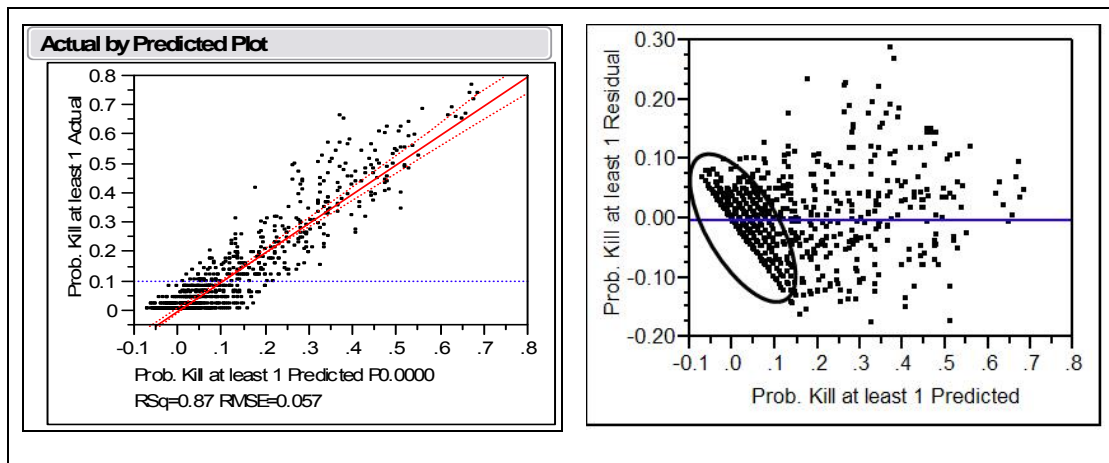
Figure 35. Actual vs. Predicted Probability to destroy at least one platform and Residual vs. Predicted Probability to destroy at least one platform.

4. Significant Interactions

In our model there are twenty statistically significant interactions between factors, but there are only eleven that are practically significant. Figure 36 shows the twenty-one interaction plots of the seven most important factors. We used the interaction profiles plot of JMP 5.1.2 to examine the interactions more closely. The plot itself shows the seven terms in the model that have significant interactions. An "interaction" means a change in the response (the probability of destroying at least one platform), caused by varying one parameter that is dependent upon another parameter. The interaction plot of Figure 36 shows the high and low levels of the factor in the row, and the trend in the probability of

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destroying at least one platform, by changing the factor in the column. The diagonal is a mirror where the axes are reversed. For example, the bottom left and upper right show the interaction between the E-2C HAWKEYE AEW and the speed of the terrorist boats. In the upper right version the high and low values of the E-2C (0 and 1) are each shown, with the trend in the probability to destroy at least one platform, as the speed of the terrorist boats changes. In the lower left version, the high and low values of the speed of the terrorist boats are shown with a trend in the probability to destroy at least one platform, as the E-2C HAWKEYE AEW is or is not present in the scenario (0 or 1).

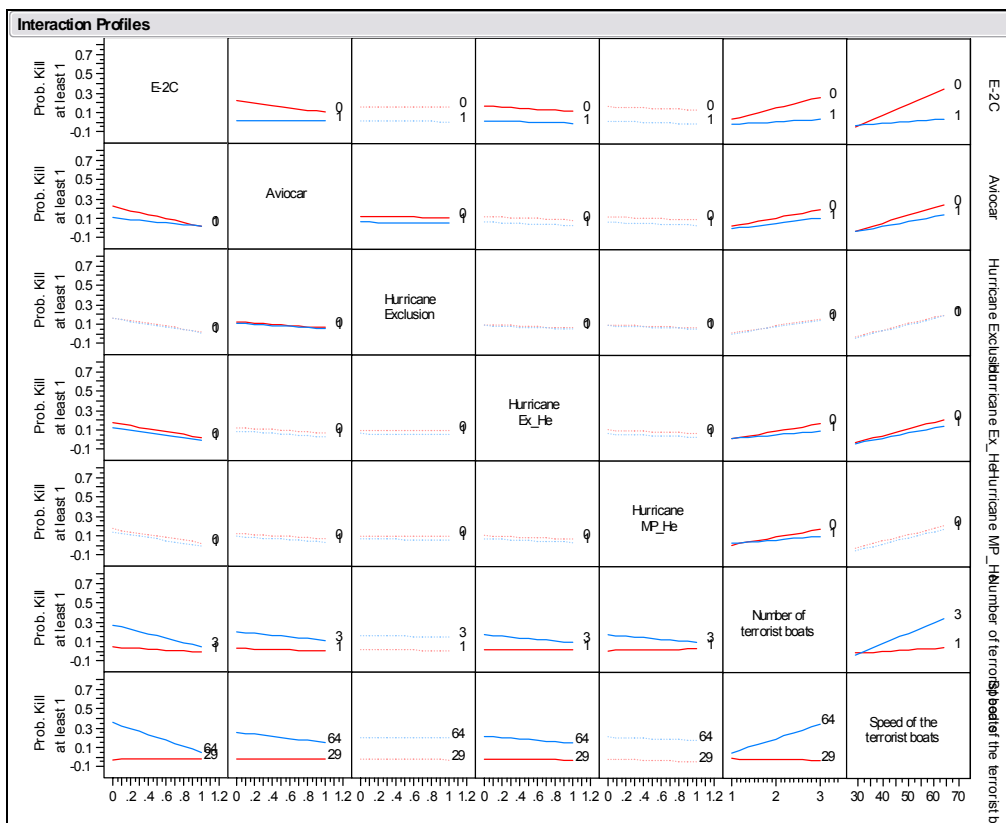Figure 36.   Interaction plot of the most significance factors in the model. (best viewed in color)

Notice in the graph (Figure 36) that there are interactions where the change in the response is more dramatic. For example, the interaction between the E-2C HAWKEYE AEW and the speed of the terrorist boats, AVIOCAR MPA, and the number of terrorist boats, and the interaction between the number of

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terrorist boats and the speed of the terrorist boats. In the first example, interpreting this into real-world terms means that the probability of destroying at least one platform when the speed of the terrorist boats is very fast is dramatically less when the E-2C HAWKEYE AEW is present in the scenario. Also, the AVIOCAR MPA adds nothing in presence of the E-2C HAWKEYE AEW. Another important example is the interaction between the number of the terrorist boats and the speed of the terrorist boats in the bottom right of the graph. In operational terms, it means that the probability of destroying at least one platform is increased when both the speed of the terrorist boats is very fast and the number of terrorist boats is more than one. Conversely, when the speed of the terrorist boats is slow (20 knots), the probability of destroying at least one platform keeps almost constant, no matter the number of terrorist boats.

C. CRITICAL CONTROLLABLE FACTORS

Because the Mexican Navy has a 24/7 operation in the Campeche Sound, protecting this critical area, and sometimes there is no detailed intelligence report of enemy capabilities and courses of actions (COA), it is necessary to have a deployment of resources that better controls for the possible enemy capabilities and COAs. The possible capabilities of the enemy for this study are the NOLH design of the noise factors explained in chapter three. To do this, we created another table with all the possible combinations of the controllable factors along with the mean of the probability to destroy at least one factor of the seventeen combinations of the noise factors. The analysis of this data includes a partition tree and a stepwise linear regression model of the critical controllable factors.

1. Partition Tree of the Controllable Factors

Figure 37 shows a regression tree of the data considering only partitions of the controllable factors (resources of the navy). This tree has a different representation: it is split in a horizontal way, so the branches split from left to right.
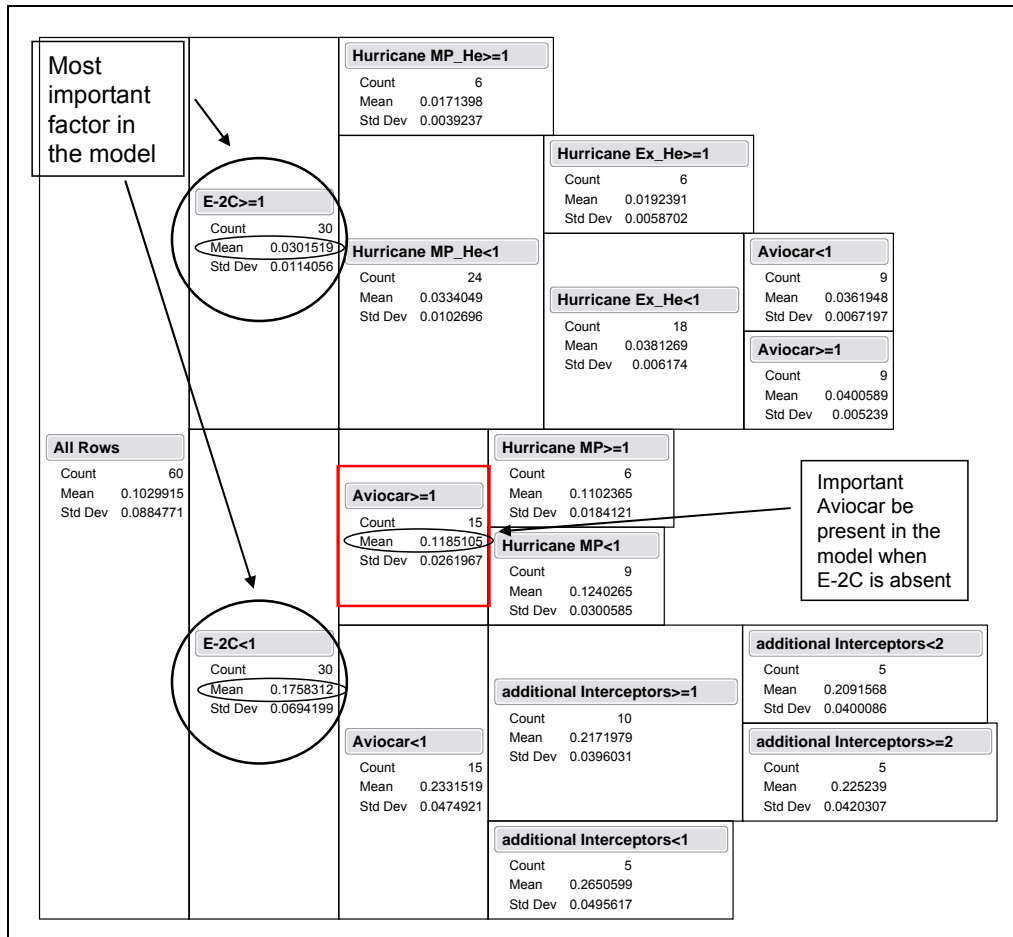
Figure 37.   Partition tree of the controllable factors in the model.

Interpreting the model is simple. Factors at the top (left) of the tree are the most important. Splits to the top are for improvements for the MOE, because the probability of destroying at least one platform is decreased. To use the tree as a prediction tool, we read the tree from left to right, following the appropriate branches (units of the navy) for the case being considered. So, for a particular scenario, we follow the branches of the units present in the area, and in the final branch, we can get the mean and standard deviation of the probability of destroying at least one platform. As stated in the full scenario, the most critical controllable factor is the presence of the E-2C HAWKEYE AEW, followed by the AVIOCAR MPA and the area patrolling of the HURACAN ship with shipborne helicopter, and, finally the addition of interceptors in the scenario.

2. Regression

The regression of the controllable factors includes the most important factors mentioned in the partition tree section. Because the factors are binary numbers (0 if the unit is not present in the scenario, and 1 otherwise), the model cannot include quadratic effects and because there is a good fit, it is not necessary to add interactions between the factors. Therefore, the regression is a linear regression model with the four most important controllable factors. Figure 38 shows the linear regression model of the most important controllable factors in the sixty possible scenarios.

Summary of Fit

RSquare	**0.845561**
RSquare Adj	**0.834329**
Root Mean Square Error	0.036013
Mean of Response	0.102992
Observations (or Sum Wgts)	60

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.39053417	0.097634	75.2820
Error	55	0.07132976	0.001297	Prob > F
C.	59	0.46186393		<.0001
Total				

Parameter Estimates

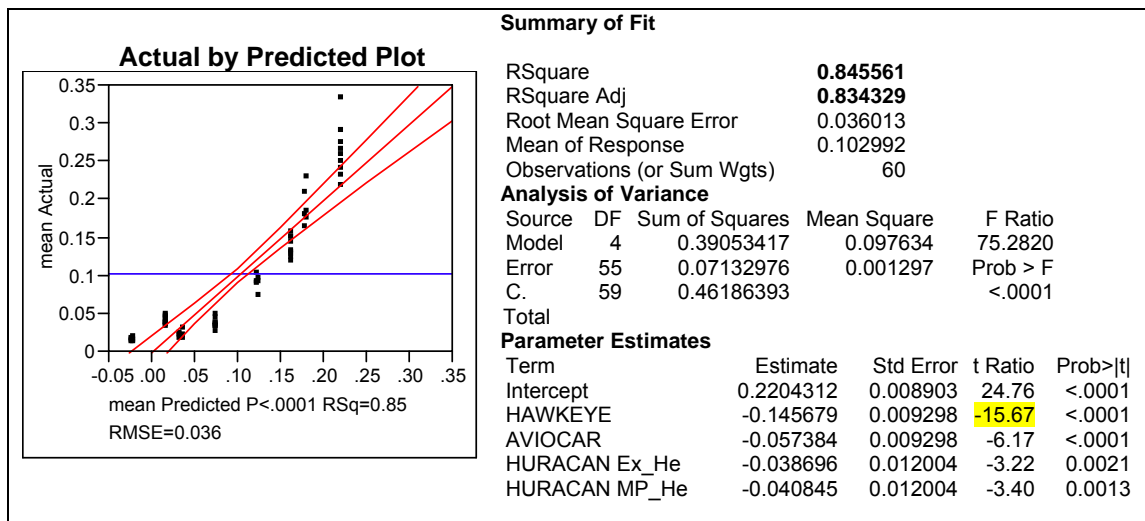| Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2204312	0.008903	24.76	<.0001
HAWKEYE	-0.145679	0.009298	-15.67	<.0001
AVIOCAR	-0.057384	0.009298	-6.17	<.0001
HURACAN Ex_He	-0.038696	0.012004	-3.22	0.0021
HURACAN MP_He	-0.040845	0.012004	-3.40	0.0013

Figure 38.   Linear regression model of the most important controllable factors.

The factors in order of priority are: the HAWKEYE AEW, the AVIOCAR MPA, the maritime prevention area patrolling of the HURACAN ship with a shipborne helicopter, and, finally the exclusion area patrolling of the HURACAN ship with a shipborne helicopter. The additional-interceptor factor is not included in the model because its *p*-value is too high, making it unnecessary in the model. The regression model explains 84.5 percent of the variability in sixty observations (twenty scenarios times the three-level factor of the additional interceptors), with an equation that contains only the four most important factors in the model.

The *t*-Ratio for "HAWKEYE AEW" (**-15.67),** is the largest value in the table and thus has the most statistical significance in examining the probability of destroying at least one platform. It is negative because there is a negatively correlated relationship (i.e., as "HAWKEYE AEW" is not present in the model the probability of destroying at least one platform increases). We can see in the table that all the t-Ratio values are negative. This is because the only factors in the model are the Navy resources; therefore all of them have negatively correlated relationship with the probability of destroying at least one platform

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VI. CONCLUSIONS

A. ANALYSIS SUMMARY

Our purpose for this research was to explore the different possible scenarios that could face the Mexican Navy while protecting the critical assets in Mexico's Campeche Sound. Each scenario differs from the others not only in respect to the resources of the Navy in the area, but also in respect to the uncontrollable factors that can be present during a terrorist attack. The study analyzes the data obtained by the simulation of multiple runs of each possible scenario of the Mexican Navy and the seventeen possible scenarios of the terrorist boats and fishing boats in the forbidden area during a terrorist attack. The data is analyzed in two parts: the full model that analyzes all the controllable and noise factors in the model and a subgroup of the data that only has the controllable factors in the model.

The study uses three analysis techniques to look at the probability that the enemy destroys at least one platform. The techniques are: classification trees, regression analysis, and the one-way analysis of the means of each of the critical factors in the model. The critical insights are summarized in two sections: one that considers all the critical factors and one that considers only with the controllable factors.

1. Critical Factors in the Full Model

The important insights found analyzing the full model are summarized in the following list:

- The most important factor in the probability of destroying at least one platform is the speed of the terrorist boats. This is because there is little time for the Navy to react against a fast boat.

- When the HAWKEYE AEW is present in the area, there is a great significant increase in the probability of destroying the terrorist boats, no matter the number and speed of the terrorist boats. This is the single most important asset of the Navy.

- The probability to kill enemy terrorist boats before they reach an oil platform decreases when more than two fishing boats are in the maritime prevention area during a terrorist boat attack. This is because they divert too many navy assets to allow the navy to sufficiently cover the area.

2.   Critical Controllable Factors

During the analysis of the data subgroup, which only includes the controllable factors (Navy resources), we perceived several important aspects of the model:

- Because of its long range surveillance radar for detection and classification, and significant communication capability, HAWKEYE AEW is the most important factor in the controllable factors.

- When the HAWKEYE AEW is absent in the scenario, it is important that the AVIOCAR MPA that serves in a very similar role as the HAWKEYE AEW (with less range in its surveillance radar) be present in the area.

- The HURACAN ship is significant in the scenarios only if it carries a shipborne helicopter.

- The patrolling area of the HURACAN ship is not important for the model. Both main patrol areas, the exclusion area and the maritime prevention area, have the same effect within the model.

- The additional intercepting boats in the area are significant in the probability to destroy the terrorist boats only if the route of the terrorist boats lies within their patrol area.

- The patrolling areas of the REDIGO aircraft and the helicopter patrolling are not significant in the model. This does not mean that they are not necessary in the scenarios; it means that any of these units' presences in the area have the same effect in the model.

B.   FOLLOW ON WORK

Following is a list of the follow-on research of value that could be accomplished using this work:

- Analysis of different enemy courses of actions (COA) and tactics.

- This study focused only on the actual resources of the Mexican Navy in the area. This model could be used to repeat the analysis while including additional Navy resources in the scenarios to see which is the best number and allocation for the units in the area.

- Analysis of factors affecting the classification of time-critical targets.

- The effects of policy changes, such as adjusting the exclusion and prevention areas.

- Analysis of the communication systems and networks among the Navy units.

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APPENDIX A.   PRELIMINARY MODEL

The first model implemented was a simple one, incorporating all possible resources in the area and the listed uncontrollable factors.

- E-2C HAWKEYE Airborne Early Warning aircraft
- C-212 AVIOCAR Maritime Patrol Aircraft
- HURACAN-class missile ship
- Aircraft type L-90 TP REDIGO
- Patrolling helicopter, type MI-17
- POLARIS Interceptor boats in the area
- Terrorist boats
- Speed of the terrorist boats
- Fishing boats in the forbidden area during a terrorist boat attack

The regression model ended up with all the above listed uncontrollable factors and the following controllable factors:

- E-2C HAWKEYE Airborne Early Warning aircraft
- C-212 AVIOCAR Maritime Patrol Aircraft
- POLARIS Interceptor boats in the area

Preliminary Regression model

Response Prob Kill at least 1

Whole Model

Summary of Fit

RSquare	0.895709
RSquare Adj	0.894791
Root Mean Square Error	0.137324
Mean of Response	0.451964
Observations (or Sum Wgts)	918

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	147.22427	18.4030	975.8781
Error	909	17.14185	0.0189	Prob > F
C. Total	917	164.36612		0.0000

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	195	11.054869	0.056692	6.6499
Pure Error	714	6.086984	0.008525	Prob > F
Total Error	909	17.141852		<.0001
				Max RSq
				0.9630

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.923575	0.023808	-38.79	<.0001
E-2C	-0.06283	0.009167	-6.85	<.0001
Aviocar	-0.091904	0.009167	-10.03	<.0001
Intercept	-0.015178	0.005551	-2.73	0.0064
Num Enemies	0.3681594	0.006338	58.09	<.0001
(Num Enemies-2.05882)*(Num Enemies-2.05882)	-0.199519	0.011836	-16.86	<.0001
Speed enemies	0.0195957	0.000352	55.66	<.0001
(Speed enemies-42.5294)*(Speed enemies-42.5294)	-0.000508	0.000038	-13.35	<.0001
Fishing ships	0.0242751	0.002976	8.16	<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
E-2C	1	1	0.885847	46.9748	<.0001
Aviocar	1	1	1.895365	100.5076	<.0001
Intercept	1	1	0.140987	7.4763	0.0064
Num Enemies	1	1	63.625398	3373.934	<.0001
Num Enemies*Num Enemies	1	1	5.358960	284.1755	<.0001
Speed enemies	1	1	58.430603	3098.464	<.0001
Speed enemies*Speed enemies	1	1	3.360711	178.2121	<.0001
Fishing ships	1	1	1.254665	66.5325	<.0001

Actual vs. Predicted Plot and Residual vs. Predicted Plot

66
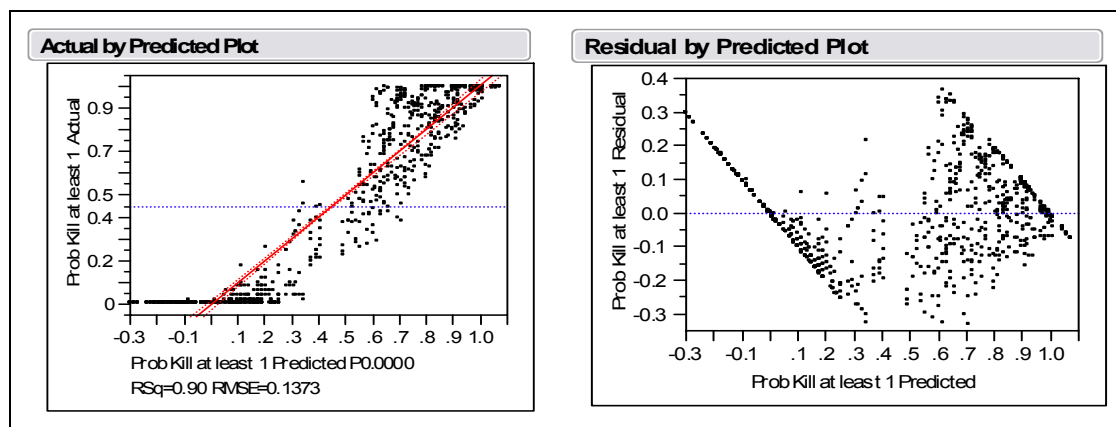
Leverage Plots of the Factors

67

Speed enemies*Speed enemies — Leverage Plot

Fishing ships — Leverage Plot
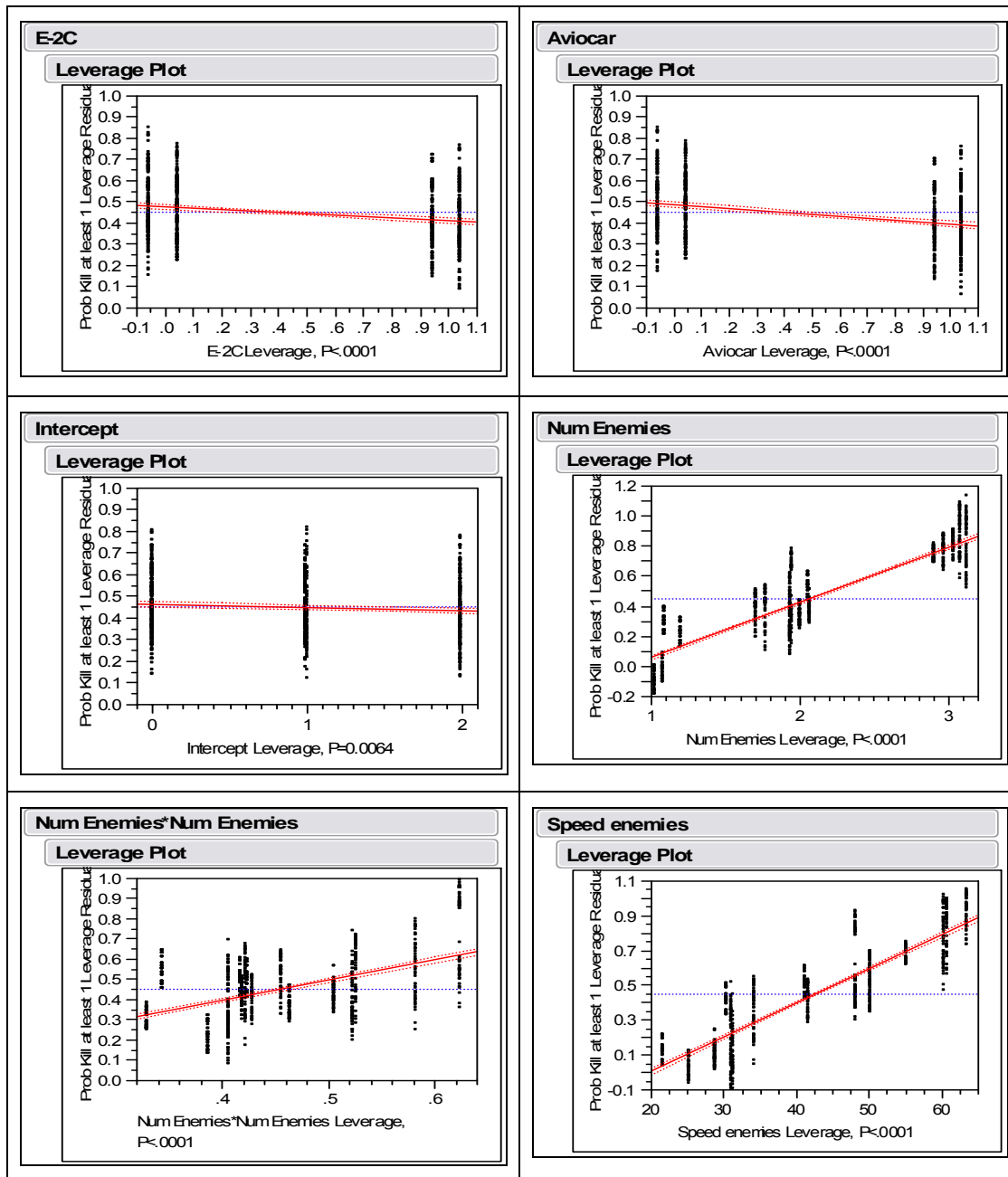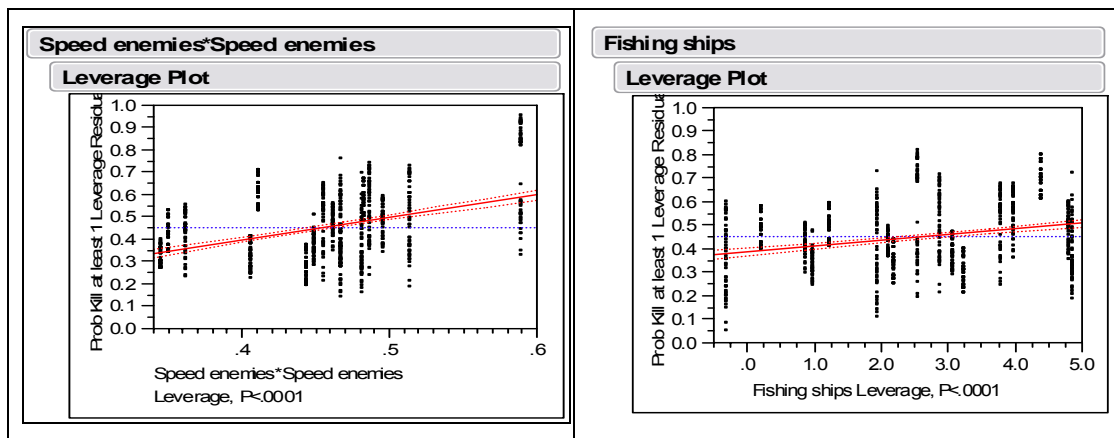
This model demonstrates that the area-patrolling of the REDIGO and the helicopter are not critical factors in all the scenarios.

LIST OF REFERENCES

Galligan, David P., Anderson, Mark A., and Lauren, Michael K., *MANA: Map Aware Non-uniform Automata Version 3.0.37 User's Manual*, New Zealand Defense Technology Agency, July 2004.

Berner, Robert A., The effective Use of Multiple Unmanned Aerial Vehicles in Surface Search and Control, Master Thesis, Naval Postgraduate School, Monterey, California, December 2004.

Winston, Wayne L., Operations Research: Applications and Algorithms, Fourth Edition, Brooks/Cole, 2004.

Montgomery, Douglas C., Peck, Elizabeth A., and Geoffrey Vining, G., Introduction to Linear Regression, third edition, Wiley-Interscience Publication, 2001.

Law, Averill, and Kelton, N. David., Simulation Modeling and Analysis, third edition, McGraw Hill, 2000.

Project Albert website, http://www.projectalbert.org, last accessed October 2005.

Sanchez, S. M. (2005), Excel Spreadsheet for Generating Nearly Orthogonal Latin Hypercube designs. Available online at http://diana.gl.nps.navy.mil/~susan/, last accessed October 2005.

Federation of American Scientists website, http://www.fas.org, last accessed September 2005.

Kleijnen, Jack P. C., Sanchez, Susan M., Lucas, Thomas W., and Cioppa, Thomas M., State-of-the-Art Review: A User Guide to the Brave New World of Designing Simulation Experiments, summer 2005.

Cioppa, Thomas M., Lucas, Thomas W., and Sanchez, Susan M., Military Applications of Agent-Based Simulations, Proceedings of the 2004 Winter Simulation Conference.

Mexican Navy website, http://www.semar.gob.mx, last accessed October 2005.

Petroleos Mexicanos website, http://www.pemex.org, last accessed July 2005.

Wikipedia web site, http://en.wikipedia.org, last accessed November 2005.

Interview with the Commander Officer and pilots of the Aerial Mexican Navy Squads based in Campeche, Campeche Mexico, July 2005.

Interview with Mexican Navy Commissioned Personnel at the Ixtoc-A platform, July 2005.

Data provided by the Semar-PEMEX Coordination, Logistic General Coordination, General Staff of the Mexican Navy, Mexico City, May 2005.

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